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Introduction to the MIPS32® 24K® Processor Core Family

The 24K® core from MIPS Technologies is a high-performance, low-power, 32-bit MIPS® RISC processor core family intended for custom system-on-silicon applications. The core is designed for semiconductor manufacturing companies, ASIC developers, and system OEMs who want to rapidly integrate their own custom logic and peripherals with a high-performance RISC processor. A 24K core is fully synthesizable to allow maximum flexibility; it is highly portable across processes and can easily be integrated into full system-on-silicon designs. This allows developers to focus their attention on end-user specific characteristics of their product.

The 24K core is ideally positioned to support new products for emerging segments of the digital consumer, network, systems, and information management markets, enabling new tailored solutions for embedded applications.

The 24K family has four members: the MIPS32® 24Kc™ core, the MIPS32 24Kc Pro™ core, the MIPS32 24Kf™ core, and the MIPS32 24Kf Pro™ core.

- The 24Kc is a 32-bit RISC core for high performance applications.
- The 24Kf core adds an IEEE-754 compliant floating point unit.
- The 24Kc Pro core offers the CorExtend® capability.
- The 24Kf Pro core has both the floating point unit and the CorExtend capability.

The term *24K core*, as used in this document, generally refers to all cores in the 24K family. When referring to characteristics unique to an individual family member, the specific core type is identified.

On a 24K core, instruction and data caches are configurable as 0, 8, 16, 32, or 64 KB in size. Each cache is organized as 4-way set associative. The data cache features non-blocking load misses. On a cache miss, the processor can continue executing instructions until a dependent instruction is reached. Both caches are virtually indexed and physically tagged. Virtual indexing allows the cache to be indexed in the same clock in which the address is generated rather than waiting for the virtual-to-physical address translation in the TLB.

The core implements the MIPS32 Release 2 Instruction Set Architecture (ISA) and the MIPS16e™ Application Specific Extension (ASE) for code compression.

The MMU of the 24K core may be TLB-based or a simple fixed mapping translation mechanism. If TLB-based, micro TLBs in the fetch and load/store units cache the latest address translations from the larger joint TLB.

The Multiply-Divide Unit (MDU) is fully pipelined and supports a maximum issue rate of one 32x32 multiply (MUL/MULT/MULTU), multiply-add (MADD/MADDU), or multiply-subtract (MSUB/MSUBU) operation per clock.

The basic Enhanced JTAG (EJTAG) features provide run control with stop, single stepping, and re-start, and with software breakpoints through the SDBBP instruction. Support for connection to an external EJTAG probe through the Test Access Port (TAP) is also included. Instruction and data virtual address hardware breakpoints as well as the MIPS Trace mechanism can be optionally included.

The bus interface implements the Open Core Protocol (OCP) [10], with 64-bit read and write data buses. The bus interface may operate at the same or a lower clock rate than the core itself.

The rest of this chapter provides an overview of the MIPS32 24K processor core and consists of the following sections:

- [Section 1.1 “24K® Core Features”](#)
- [Section 1.2 “24K® Core Block Diagram”](#)

1.1 24K® Core Features

- 8-stage pipeline
- 32-bit Address Paths
- 64-bit Data Paths to Caches
- MIPS32-Compatible Instruction Set
 - Multiply-add and multiply-subtract instructions (MADD, MADDU, MSUB, MSUBU)
 - Targeted multiply instruction (MUL)
 - Zero and one detect instructions (CLZ, CLO)
 - Wait instruction (WAIT)
 - Conditional move instructions (MOVZ, MOVN)
 - Prefetch instruction (PREF)
- MIPS32 Enhanced Architecture (Release 2) Features
 - Vectored interrupts and support for an external interrupt controller
 - Programmable exception vector base
 - Atomic interrupt enable/disable
 - GPR shadow sets
 - Bit field manipulation instructions
- MIPS16e Application Specific Extension
 - 16 bit encodings of 32-bit instructions to improve code density
 - Special PC-relative instructions for efficient loading of addresses and constants
 - Data type conversion instructions (ZEB, SEB, ZEH, SEH)

- Compact jumps (JRC, JALRC)
- Stack frame set-up and tear down “macro” instructions (SAVE and RESTORE)
- Programmable L1 Cache Sizes
 - Individually configurable instruction and data caches
 - Sizes of 0, 8, 16, 32, or 64 KB
 - 4-Way set associative
 - Up to 9 non-blocking loads
 - Data cache supports Write-back with write-allocation and Write-through without write-allocation
 - 256-bit (32-byte) cache line size, doubleword sector - suitable for standard single-port SRAM
 - Cache line locking support
 - Non-blocking prefetches
- Data and Instruction ScratchPad RAMs
 - Separate RAMs for Instruction and Data
 - Addressable up to 1MB
 - 64-bit OCP interfaces for external access
- R4000 Style Privileged Resource Architecture
 - Count/compare registers for real-time timer interrupts
 - Instruction and data watch registers for software breakpoints
- Standard Memory Management Unit
 - 16/32/64 dual-entry MIPS32-style JTLB with variable page sizes
 - 4 entry instruction TLB
 - 8-entry data TLB
- Optional Memory Management Unit
 - Simple Fixed Mapping Translation (FMT)
 - Address spaces mapped using register bits
- OCP Bus Interface Unit (BIU)
 - 32b address and 64b data

- Flexible core/bus clock ratios
- Supports bursts of 4x64b
- 4 entry write buffer - handles eviction data, write-through, uncached, and uncached accelerated store data
- Simple Byte enable mode allows easier bridging to other bus standards
- Extensions for management of front side L2 cache
- CorExtend® User Defined Instruction capability (24Kc Pro and 24Kf Pro)
 - Optional support for the CorExtend feature allows users to define and add instructions to the core (as a build-time option)
 - Single- or multi-cycle instructions
 - Source operations from register, immediate field, or local state
 - Destination to a register or local state
 - Interface to multiply-divide unit, allowing sharing of accumulation registers
- Multiply-Divide Unit
 - Maximum issue rate of one 32x32 multiply per clock
 - Early-in divide control. Minimum 11, maximum 34 clock latency on divide
- Floating Point Unit (24Kf and 24Kf Pro only)
 - IEEE-754 compliant floating point unit
 - Compliant to MIPS 64b FPU standards
 - Supports single and double precision datatypes
- Coprocessor2 Interface
 - 64-bit interface to user designed coprocessor
- Power Control
 - No minimum frequency
 - Power-down mode (triggered by WAIT instruction)
 - Support for software-controlled clock divider
 - Support for extensive use of fine-grain clock gating
- EJTAG Debug Support

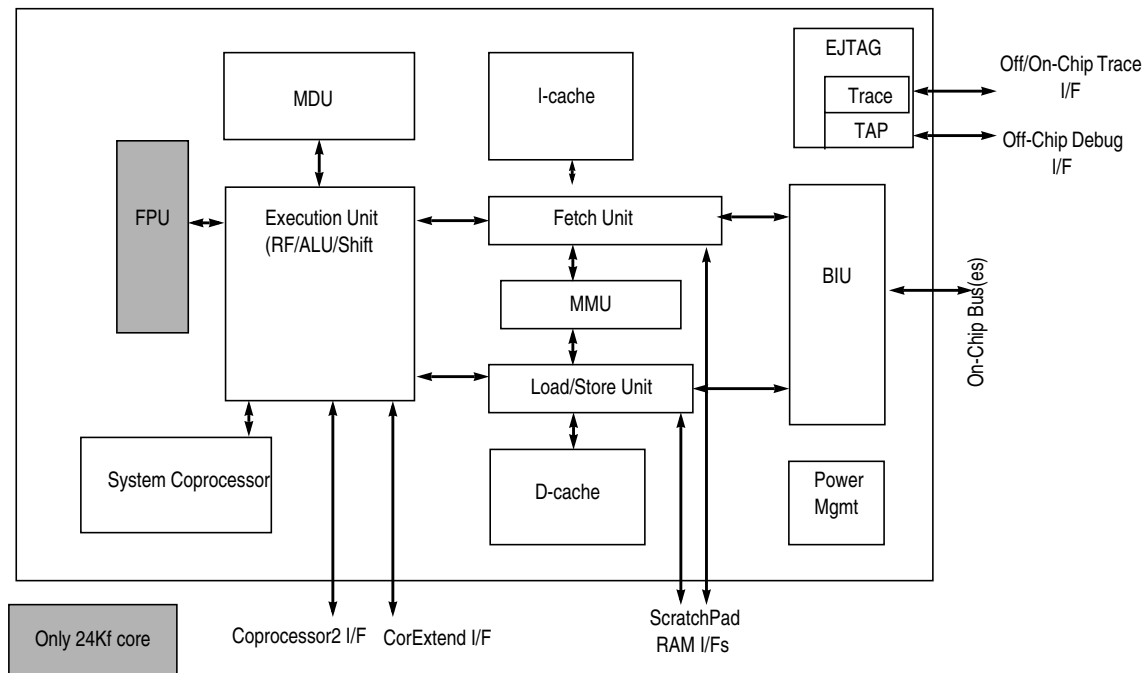
- Start, stop, and single stepping control
- Software breakpoints via the SDBBP instruction
- Optional hardware breakpoints on virtual addresses; 0 or 4 instruction and 0 or 2 data breakpoints
- Test Access Port (TAP) facilitates high speed download of application code
- Optional MIPS Trace hardware to enable real-time tracing of executed code

1.2 24K® Core Block Diagram

The 24K core contains a number of blocks, as shown in the block diagram in [Figure 1.1](#). The major blocks are as follows:

- Execution Unit (ALU)
- Multiply-Divide Unit (MDU)
- System Control Coprocessor (CP0)
- Memory Management Unit (MMU)
- Floating Point Unit (FPU) - only in 24Kf
- Cache Controller
- Bus Interface Unit (BIU)
- Power Management
- MIPS16e support
- Instruction Cache (I-cache)
- Data Cache (D-cache)
- Enhanced JTAG (EJTAG) Controller
- CorExtend® User Defined Instructions (UDI)

[Figure 1.1](#) shows a block diagram of a 24K core. The MMU can be implemented using either a translation lookaside buffer or a fixed mapping (FMT). Refer to [Chapter 4, “Memory Management of the 24K® Core”](#) on page 87 for more information.

Figure 1.1 24K® Processor Core Block Diagram

1.2.1 Logic Blocks

The following subsections describe the various logic blocks of the 24K processor core.

1.2.1.1 Execution Unit

The core execution unit implements a load-store architecture with single-cycle Arithmetic Logic Unit (ALU) operations (logical, shift, add, subtract) and an autonomous multiply-divide unit. The core contains thirty-two 32-bit general-purpose registers (GPRs) used for scalar integer operations and address calculation. Optionally, one or three additional register file shadow sets (each containing thirty-two registers) can be added to minimize context switching overhead during interrupt/exception processing. The register file consists of two read ports and one write port and is fully bypassed to minimize operation latency in the pipeline.

The execution unit includes:

- 32-bit adder used for calculating the data address
- Logic for branch determination and branch target address calculation
- Bypass multiplexers used to avoid stalls when executing instruction streams where data-producing instructions are followed closely by consumers of their results
- Zero/One detect unit for implementing the CLZ and CLO instructions
- ALU for performing bitwise logical operations
- Shifter and Store aligner

- Floating Point Unit Interface
- Coprocessor2 Interface

1.2.1.2 Multiply/Divide Unit (MDU)

The Multiply/Divide unit performs multiply and divide operations. The MDU consists of a pipelined 32x32 multiplier, result-accumulation registers (HI and LO), multiply and divide state machines, and all multiplexers and control logic required to perform these functions. This pipelined MDU supports execution of a multiply or multiply-accumulate operation every clock cycle. Unlike previous cores, there is no dependence between operand size and issue rate for multiplies. Divide operations are implemented with a simple 1 bit per clock iterative algorithm and require 35 clock cycles in worst case to complete. Early-in to the algorithm detects sign extension of the dividend, if it is actual size is 24, 16 or 8 bit. the divider will skip 7, 15 or 23 of the 32 iterations. An attempt to issue a subsequent MDU instruction while a divide is still active causes a pipeline stall until the divide operation is completed.

On Pro Series cores, the MDU accumulator is accessible from the CorExtend block. Many CorExtend instruction types can make use of the HI/LO accumulation registers.

1.2.1.3 System Control Coprocessor (CP0)

In the MIPS architecture, CP0 is responsible for the virtual-to-physical address translation, cache protocols, the exception control system, the processor's diagnostics capability, operating mode selection (kernel vs. user mode), and the enabling/disabling of interrupts. Configuration information such as cache size, set associativity, and presence of build-time options are available by accessing the CP0 registers. Refer to [Chapter 6, "CP0 Registers of the 24K® Core"](#) on page 146 for more information on the CP0 registers. Refer to [Chapter 11, "EJTAG Debug Support in the 24K® Core"](#) on page 240 for more information on EJTAG debug registers.

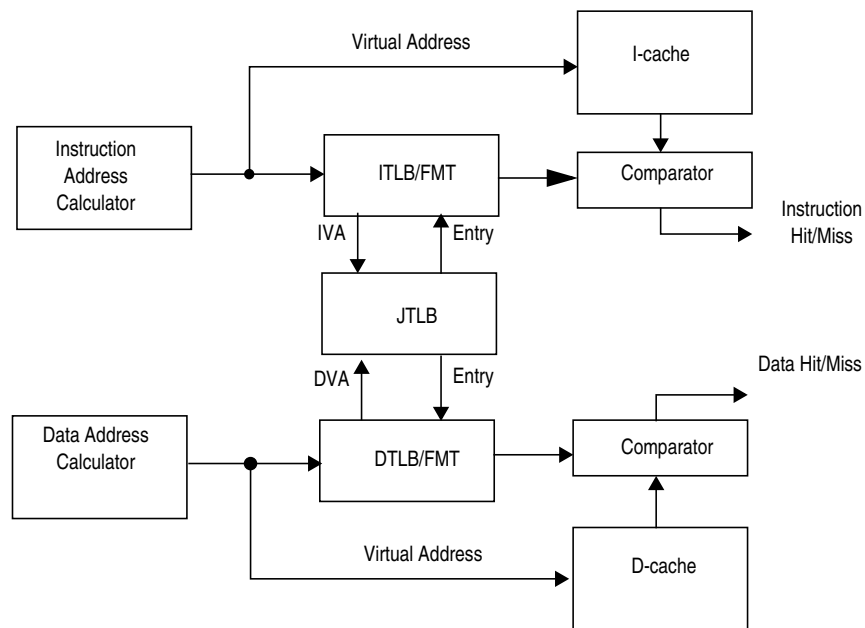
1.2.1.4 Memory Management Unit (MMU)

The 24K core contains an MMU that interfaces between the execution unit and the cache controllers, shown in [Figure 1.2](#). Although the 24K core implements a 32-bit architecture, the Memory Management Unit (MMU) is modeled after the MMU found in the 64-bit R4000 family, as defined by the MIPS32 architecture.

On the 24K core, by default the MMU is based on a Translation Lookaside Buffer (TLB). The TLB consists of three translation buffers: a configurable 16/32/64 dual-entry fully associative Joint TLB (JTLB), a 4 entry fully associative Instruction TLB (ITLB) and a 8-entry fully associative data TLB (DTLB). The ITLB and DTLB, also referred to as the micro TLBs, are managed by the hardware and are not software visible. The micro TLBs contain subsets of the JTLB. When translating addresses, the corresponding micro TLB (I or D) is accessed first. If there is not a matching entry, the JTLB is used to translate the address and refill the micro TLB. If the entry is not found in the JTLB, then an exception is taken.

The core optionally implements a FMT-based MMU instead of a TLB-based MMU. The FMT replaces the ITLB and DTLB and the JTLB is removed. The FMT performs a simple translation to get the physical address from the virtual address. Refer to [Chapter 4, "Memory Management of the 24K® Core"](#) on page 87 for more information on the FMT.

[Figure 1.2](#) shows how the address translation mechanism interacts with cache accesses.

Figure 1.2 Address Translation During a Cache Access

1.2.1.5 Fetch Unit

The fetch unit is responsible for providing instructions to the execution unit. The fetch unit includes:

- Control logic for the instruction cache
- MIPS16e instruction recoder
- Dynamic branch prediction
 - 512-entry bimodal branch history table for predicting conditional branches
 - 4-entry return prediction stack for predicting return addresses
- 8-entry instruction buffer to decouple the fetch and execution pipelines
- Interface to Instruction ScratchPad RAM

1.2.1.6 Instruction Cache

The instruction cache is an on-chip memory array of up to 64 KB. The cache is virtually indexed and physically tagged, allowing the virtual-to-physical address translation to occur in parallel with the cache access rather than having to wait for the physical address translation. The tag holds 20 or 21 bits of the physical address, a valid bit, a lock bit, and optionally a parity bit. There is a separate 6b array which holds data for all 4 ways to be used in the Least Recently Used (LRU) replacement scheme. Some precode information is included in the instruction cache data array. An additional 6b per pair of 32b instructions is used to enable quick detection of branches and jumps in the fetch unit. If parity is implemented, a single bit covers the 6b precode and 8b cover the 64b data.

The core supports instruction cache locking. Cache locking allows critical code to be locked into the cache on a “per-line” basis, enabling the system designer to maximize the efficiency of the system cache. Cache locking is

always available on all instruction cache entries. Entries can be marked as locked or unlocked (by setting or clearing the lock bit) on a per-entry basis using the CACHE instruction.

The LRU array must be bit-writable. The tag and data arrays only need to be word-writable.

1.2.1.7 Load/Store Unit

The Load/Store Unit is responsible for data loads and stores. It includes:

- Data cache control logic
- 4 line fill/store buffer
- ScratchPad RAM interface

1.2.1.8 Data Cache

The data cache is an on-chip memory array of up to 64 KB. The cache is virtually indexed and physically tagged, allowing the virtual-to-physical address translation to occur in parallel with the cache access. The tag holds 20 or 21 bits of the physical address, a valid bit, a lock bit, and optionally a parity bit. A separate array holds the LRU bits (6b), dirty bits (4b), and optionally, dirty parity bits (4b) for all 4 ways. The data array is optionally parity protected with 1b per 8b of data.

In addition to instruction cache locking, all cores also support a data cache locking mechanism identical to the instruction cache, with critical data segments to be locked into the cache on a “per-line” basis. The locked contents cannot be selected for replacement on a cache miss, but can be updated on a store hit.

Cache locking is always available on all data cache entries. Entries can be marked as locked or unlocked on a per-entry basis using the CACHE instruction.

The physical data cache memory must be byte writable to support sub-word store operations. The LRU/dirty bit array must be bit-writable.

1.2.1.9 Bus Interface Unit (BIU)

The Bus Interface Unit (BIU) controls the external interface signals. Additionally, it contains the implementation of a collapsing write buffer. This buffer is used to merge Write-Through transactions as well as to gather multiple writes together from dirty line evictions and uncached accelerated stores. The write buffer consists of 4 32B entries.

1.2.1.10 Power Management

The core offers a number of power management features, including low-power design, active power management, and power-down modes of operation. The core is a static design that supports slowing or stopping the clocks to reduce power.

A register-controlled power management mode in the core provides three bits in the CP0 Status register for software control of the power management function and allows interrupts to be serviced even when the core is in power-down mode.

An instruction-controlled power-down mode is entered by execution of the WAIT instruction and is used to invoke low-power mode.

coreRefer to [Chapter 9, “Power Management in the 24K® Core”](#) on page 232 for more information on power management.

1.2.1.11 MIPS16e™ Application Specific Extension

The 24K core includes support for the MIPS16e ASE. This ASE improves code density through the use of 16-bit encodings of MIPS32 instructions plus some MIPS16e-specific instructions. PC relative loads allow quick access to constants. Save/Restore macro instructions provide for single instruction stack frame setup/teardown for efficient subroutine entry/exit. Sign- and zero-extend instructions improve handling of 8bit and 16bit datatypes.

A decompressor converts the MIPS16e 16-bit instructions fetched from the instruction cache or external interface back into 32-bit instructions for execution by the core.

Refer to the *MIPS32® Architecture For Programmers, Volume IV-a: The MIPS16e™ Application-Specific Extension to the MIPS32® Architecture* [3] and to [Chapter 4, “The MIPS® DSP Application-Specific Extension to the MIPS32® Instruction Set”](#) on page 99 for more information on the features of the MIPS16e ASE.

1.2.1.12 EJTAG Debug

All cores provide basic EJTAG support with debug mode, run control, single step, and software breakpoint instruction (SDBBP) as part of the core. These features allow for the basic software debug of user and kernel code. A TAP controller is also included, enabling communication with an external EJTAG probe through a dedicated port. This provides the possibility for debugging without debug code in the application, and for download of application code to the system.

An optional EJTAG feature is hardware breakpoints. A 24K core may have four instruction breakpoints and two data breakpoints, or no breakpoints. The hardware instruction breakpoints can be configured to generate a debug exception when an instruction is executed anywhere in the virtual address space. Bit mask and Address Space Identifier (ASID) values may apply in the address compare. These breakpoints are not limited to code in RAM like the software instruction breakpoint (SDBBP). The data breakpoints can be configured to generate a debug exception on a data transaction. The data transaction may be qualified with both virtual address, data value, size and load/store transaction type. Bit mask and ASID values may apply in the address compare, and byte mask may apply in the value compare.

Another optional debug feature is support for MIPS Trace that enables real-time tracing capability. The trace information can be stored to either an on-chip trace memory or an off-chip trace probe. The trace of program flow is highly flexible and can include the instruction program counter as well as data addresses and data values. The trace features can provide a powerful software debugging mechanism.

Refer to the *EJTAG Specification* [11] and to [Chapter 11, “EJTAG Debug Support in the 24K® Core”](#) on page 240 for more information on the EJTAG features.

1.2.1.13 CorExtend® User Defined Instructions

This optional module contains support for CorExtend user defined instructions. These instructions must be defined at build-time for the 24K core. The CorExtend feature is a capability of the 24Kc Pro and 24Kf Pro cores. This feature makes 16 instructions in the opcode map available for customer usage, and each instruction can have single or multi-cycle latency. A CorExtend instruction can operate on any one or two general-purpose registers or immediate data contained within the instruction, and can write the result of each instruction back to a general purpose register or a local register. Implementation details for CorExtend can be found in the *CorExtend® Instruction Integrator's Guide for MIPS32® Cores* [8].

Refer to [Section Table 12.5 “MIPS32 SPECIAL2 Encoding of Function Field”](#) for a specification of the opcode map available for user defined instructions.

Pipeline of the 24K® Core

The 24K processor core implements an 8-stage pipeline. The pipeline allows the processor to achieve high frequency while minimizing device complexity, reducing both cost and power consumption. This chapter contains the following sections:

- [Section 2.1 “Pipeline Stages”](#)
- [Section 2.2 “Instruction Fetch”](#)
- [Section 2.3 “Load Store Unit”](#)
- [Section 2.4 “MDU Pipeline”](#)
- [Section 2.5 “Skewed ALU”](#)
- [Section 2.6 “Interlock Handling”](#)
- [Section 2.7 “Instruction Interlocks”](#)
- [Section 2.8 “Hazards”](#)

2.1 Pipeline Stages

The pipeline consists of eight stages:

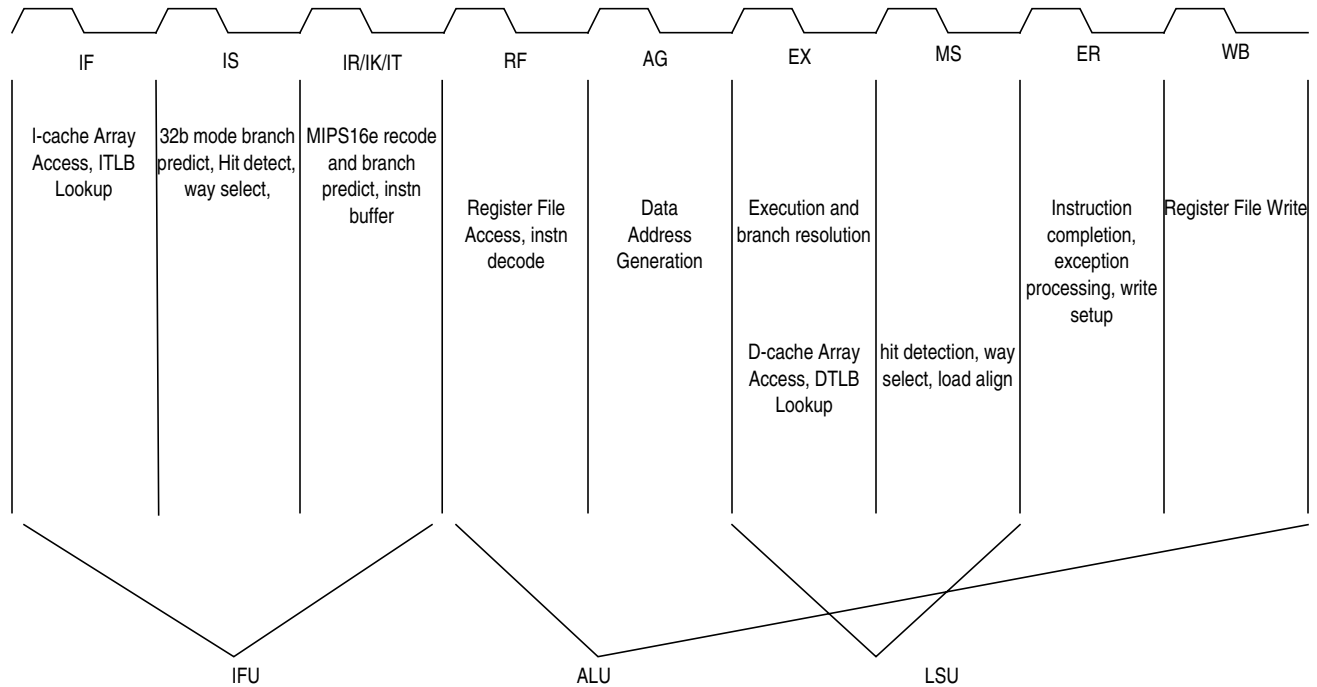
- IF - Instruction fetch First
- IS - Instruction fetch Second
- IR - Instruction recode (MIPS16e only)
- IK - Instruction kill (MIPS16e only)
- RF - Register File
- AG - Address Generation
- EX - EXecute
- MS - Memory Second
- ER - Exception Resolution
- WB - WriteBack

Pipeline of the 24K® Core

Three additional stages are conditionally added to the fetch pipeline after the IS stage when executing MIPS16e code. The IR and IK stages are generally bypassed while executing 32-bit code.

Figure 2.1 shows the basic pipeline organization. The various parts of the pipeline are described in more detail in this chapter.

Figure 2.1 24K® Core Pipeline Stages



2.1.1 IF Stage: Instruction Fetch First

- I-cache tag/data arrays accessed
- Branch History Table accessed
- ITLB address translation performed
- EJTAG break/watch compares done

2.1.2 IS - Instruction Fetch Second

- Detect I-cache hit
- Way select
- MIPS32 Branch prediction

2.1.3 IR - Instruction Recode (MIPS16e only)

- MIPS16 recode
- MIPS16 branch prediction
- Stage is bypassed when executing MIPS32 code

2.1.4 IK - Instruction Kill (MIPS16e only)

- Kill MIPS16 instructions (due to branches as an example)
- Stage is bypassed when executing MIPS32 code

2.1.5 IT - Instruction Fetch Third

- Stage is bypassed when executing MIPS32 code and the instruction buffer is empty
- Instruction Buffer
- Branch target calculation

2.1.6 RF - Register File Access

- Register File access
- Instruction decoding/dispatch logic
- Bypass muxes

2.1.7 AG - Address Generation

- D-cache Address Generation
- Bypass muxes

2.1.8 EX - Execute/Memory Access

- Skewed ALU
- DTLB
- Start DCache access
- Branch Resolution

2.1.9 MS - Memory Access Second

- Complete DCache access
- DCache hit detection

- Way select mux
- Load align

2.1.10 ER- Exception Resolution

- Instruction completion
- Register file write setup
- Exception processing

2.1.11 WB - Writeback

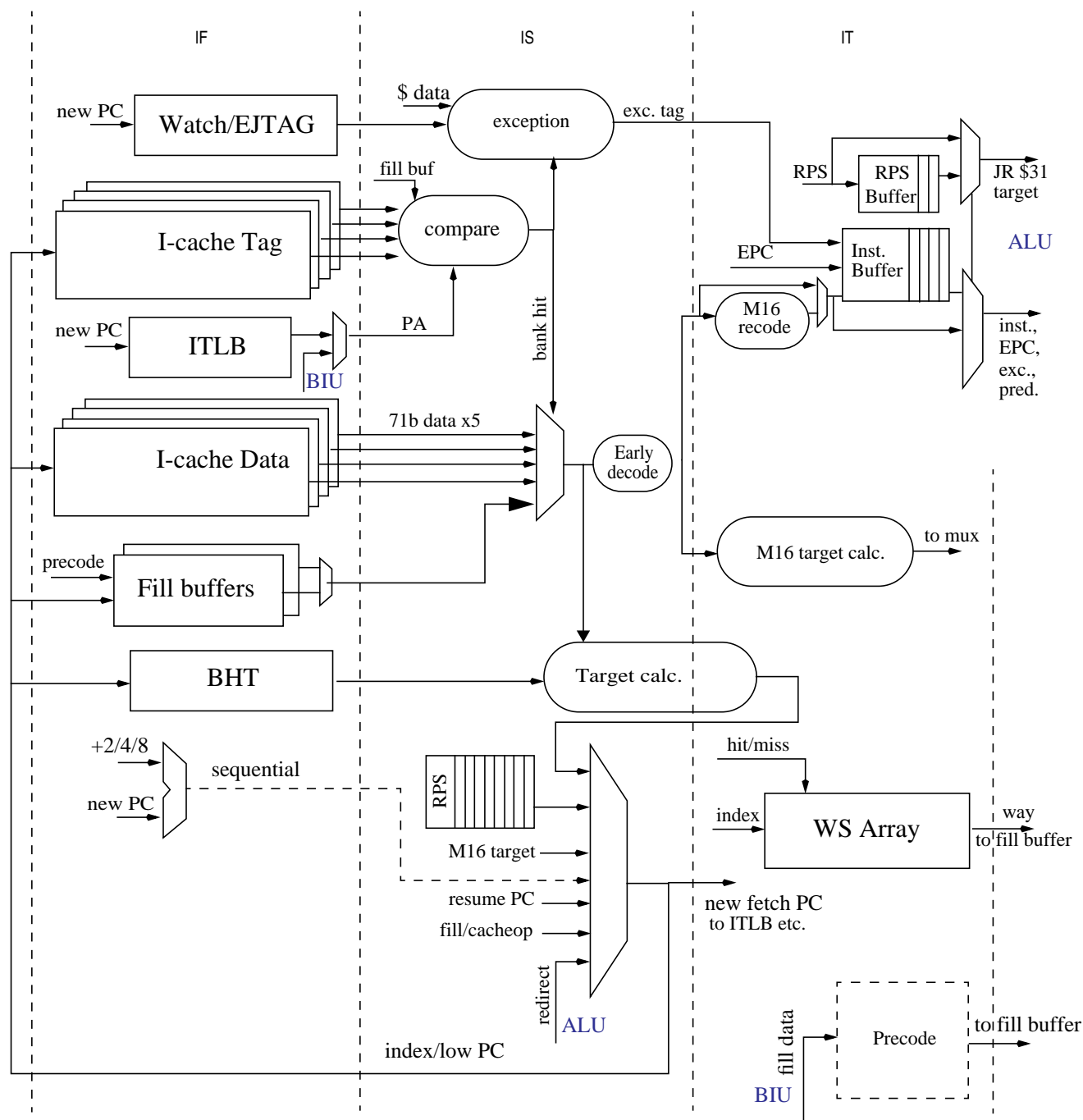
- Register file writeback occurs on rising edge of this cycle

2.2 Instruction Fetch

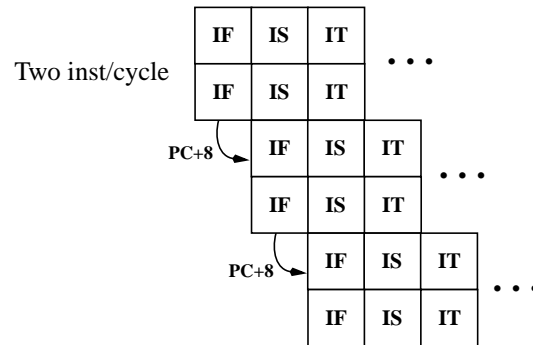
The IFU is responsible for supplying instructions to the execution units and handling the results of all control transfer instructions (branches, jumps, etc.). The IFU operation encompasses four pipe stages: IF (Instruction fetch First), IS (Instruction fetch Second), IR (Instruction Recode) and IK (Instruction Kill). The instruction cache tags and data are accessed in IF, and the hit determination and the first part of the 32-bit mode target calculation is done in IS. The IR and IK stage handle MIPS16e recoding. The remainder of the 32-bit mode target calculation as well as instruction buffering to the ALU is done in the IT stage, but can be bypassed during 32-bit mode if the instruction buffer is empty. This instruction buffering decouples the IFU from the rest of the pipeline, allowing fetches to proceed even if the processor execution is stalled for some reason. The fetch pipeline and cache bandwidth is 64 bits, supplying up to two instructions per cycle in MIPS32 mode, which allows the IFU to get ahead of the ALU and shields the execution pipeline from some IFU miss penalties.

Figure 2.2 shows the general datapath of the IFU along with major structures.

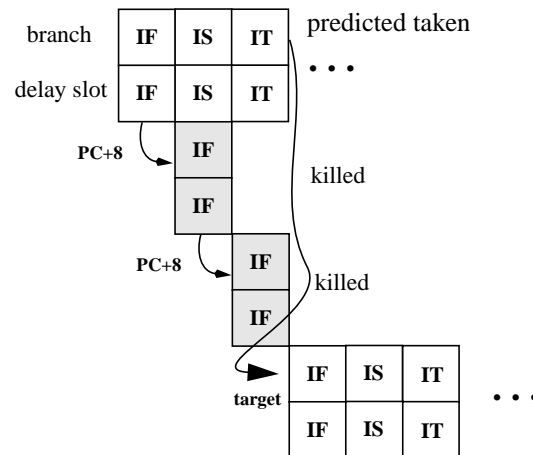
Figure 2.2 IFU Block Diagram



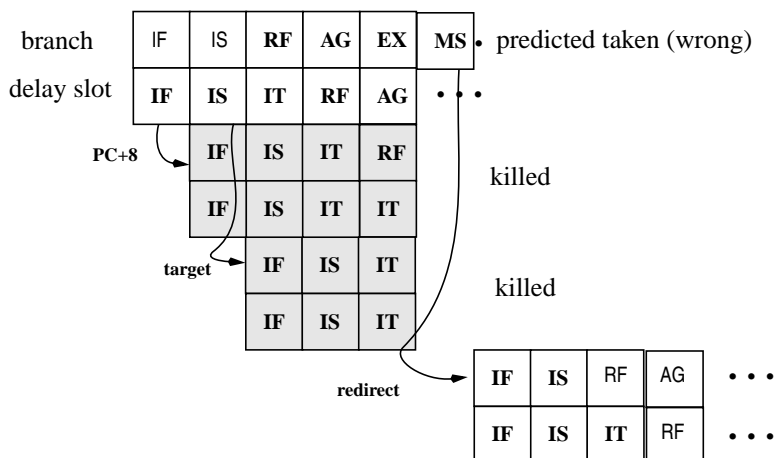
The following diagrams illustrate the timing of various IFU operations. The simplest of these is the sequential fetch path, in which the next fetch PC is incremented by 8 bytes in parallel with the cache lookup. If each fetch hits in the cache, the IFU can provide two instructions per cycle and will quickly fill up the instruction buffer, after which it will stall based on a buffer full signal.

Figure 2.3 Timing of 32-bit Mode Sequential Fetches

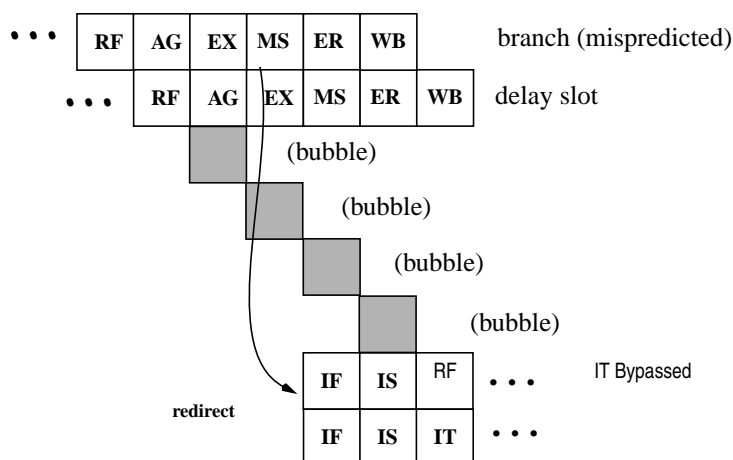
Another common situation is a control transfer instruction (branch/jump). The calculation of the target for 32-bit mode instructions starts in the IS stage, but does not complete until the IT stage. For a predicted taken path this means that if the delay slot of that branch is in the same fetch bundle, there will be a 2 cycle bubble since the sequential fetches will not be used. If the delay slot is in the next fetch bundle, there will be a 1 cycle bubble.

Figure 2.4 Timing of 32-bit Mode Branch Taken Path

For conditional branches, the control transfer is most likely speculative, based upon the branch history table. The resolution of this branch by the ALU will be calculated in the EX stage and will be used by the IFU in the MS stage, resulting in a several-cycle fetch bubble. The following figure illustrates one possibility assuming the instruction buffer is empty and the delay slot is in the same fetch bundle.

Figure 2.5 Fetch Timing of 32-bit Mode Branch Mispredict

The delay slot and the IT stage bypass lessens the impact of a mispredict on the execution pipeline, though. Assuming no stalls, the ALU sees a four-cycle bubble:

Figure 2.6 Execution Timing of 32-bit Mode Branch Mispredict

2.2.1 Branch History Table

A branch history table (BHT) will be accessed in parallel with the cache in the IF stage. This table is a 512-entry bimodal predictor. The table is indexed with bits 11:3 of the VA and each entry contains a two bit saturating counter that indicates whether a branch is taken or not. The indexing is down to bit 3 because in 32b code there can only be one branch every 64b because of the branch delay slot. In MIPS16e code, the smaller instructions and lack of delay slots means that up to 4 branches can exist within a 64b fetch bundle and will share the same BHT entry. However, in typical code, the branch density is lower than in 32b code and keeping the same 64b indexing maintains reasonable prediction accuracy.

Unlike some previous MIPS processors, the 24K core uses the BHT to predict branch likely instructions. Architecturally, these are specified to only be used when a branch is taken > 95% of the time. However, the default settings of

many compilers use these even when that is not the case. The delay slot characteristics (the delay slot is only executed if the branch is taken) allow a useful instruction to be placed in the delay slot instead of a NOP. When used in this fashion, dynamic prediction is much more accurate than statically predicting a branch likely as taken.

Unconditional branches (BEQ r0, r0 and BGEZAL r0) are detected by the precode logic and will be statically predicted taken, bypassing the BHT.

The ALU verifies the correctness of the prediction when the branch reaches the EX stage. In the case of a mispredict, the instructions on the mispredicted path will be killed and the fetch will be redirected to the correct instruction. This will cause a 4 cycle bubble in the pipeline.

2.2.1.1 Branch Target Calculation

Branch target calculation is done in the IT stage. This alleviates a critical timing path in the IFU and removes the need for replicating the branch target logic on all 4 ways of the cache. In the case of a jump or a branch that is predicted taken, subsequent fetches will be killed (after the fetch of the delay slot). This added cycle is generally covered by the instruction buffer. A string of taken branches will slowly drain the instruction buffer as only two instructions are fetched every three cycles.

2.2.2 Return Prediction Stack

The return prediction stack (RPS) is a simple stack to hold return addresses. Every time a JAL, JALR ra, or BGEZAL is seen, the link address is pushed onto the stack. When a JR ra is executed, a link address is popped off of the stack. If calling convention is maintained and the stack doesn't overflow, this will have very high prediction accuracy. The RPS contains 4 entries.

The ALU will verify the correctness of the prediction in the EX stage. If the prediction was wrong, the fetch will be redirected in the MS stage and there will be a 4 cycle bubble from the misprediction.

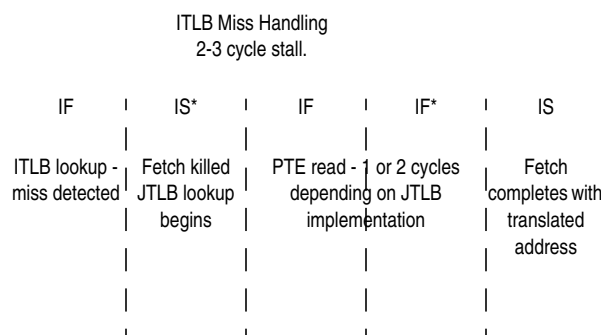
JR that don't use ra are not predicted. The IFU will stall until the ALU reads the register file. The timing on this will be the same as for a return mispredict.

2.2.3 ITLB

The IFU relies on a small subset of TLB entries stored locally in a four-entry ITLB to translate the PC into a physical address for tag comparison. The ITLB stores mappings for 4KB or 1MB pages or sub-pages (i.e. if the JTLB page is 64KB, only the 4KB sub-page containing the desired virtual address will be mapped into the ITLB). The ITLB access occurs in parallel with the primary cache lookup. If there is a miss in the ITLB, the BIU must look up the entry in the main JTLB.

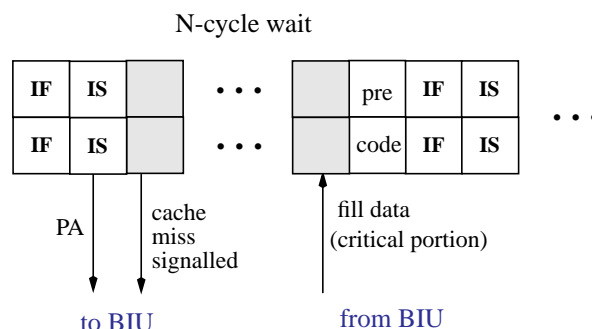
A miss in the ITLB will be detected in the IF stage, and the IFU will kill that fetch. The virtual address and the miss indication will be sent to the BIU during IF, allowing the JTLB to start a lookup in the next cycle. The latency of the JTLB lookup can be impacted by several factors. The JTLB can be busy processing a DTLB miss or a TLB operation, delaying the start of the JTLB lookup. Also, the JTLB access time depends on how it is implemented. An SRAM-based PFN array will take an extra cycle over a flop-based version, yielding a 3 cycle latency instead of 2. The fetch will be restarted when the JTLB indicates that data is going to be returned.

The cache coherence attributes can be reduced to one bit (uncached/cached) for the instruction cache. An ITLB entry will also record the associated JTLB entry, so that for a JTLB write, the ITLB can invalidate its copy if present. The ITLB uses a true LRU replacement algorithm.

Figure 2.7 Timing of an ITLB Miss

2.2.4 Cache Miss Timing

A miss in the instruction cache will be detected in the IS stage. The IFU will allocate one of the entries in the fill buffer and send the translated physical address and the miss indication to the BIU during the next cycle. The IFU will then enter an idle state and, assuming no redirect event, will replay the IF stage once the data returns from the BIU. Prior to writing into the cache, the IFU precodes the instructions with some additional information about branches/jumps that help speed up fetch unit processing of those instructions. Precoding the instructions and the write into the fill buffer will happen in the cycle the BIU returns the data, and in the following IF stage the data can be bypassed from the fill buffer. Thus, the IFU portion of the cache miss penalty is normally 4 cycles. The total miss penalty could range from a minimum of 10-12 cycles for an L2 hit to 50 or more for an access to main memory.

Figure 2.8 Timing of a Cache Miss

2.2.5 MIPS16e™

The IFU is responsible for recoding MIPS16e instructions. Before the MIPS16e instruction is sent to the ALU, it is recoded into a 32b instruction. Some additional state is used for the MIPS16e instructions that does not have a direct counterpart in the MIPS32 instruction set (such as PC-relative loads and adds). This recoding step is handled in an additional pipeline stage that is only active when executing MIPS16e code.

In each cycle, the recode logic processes 32b of the instruction stream and puts 1-2 instructions in the fetch buffer. Many instructions can be generated two at a time, but there are two exceptions: JAL(X) and EXTENDED instructions are 32b. When the JAL(X) is in the 32b fetch window, it will be recoded in one cycle. If the JAL(X) starts in the middle of a fetch window, the first instruction will be recoded in the first cycle, and the fetch window will be shifted so the JAL(X) can be recoded in the second cycle. EXTENDs are handled the same way—the EXTEND and the

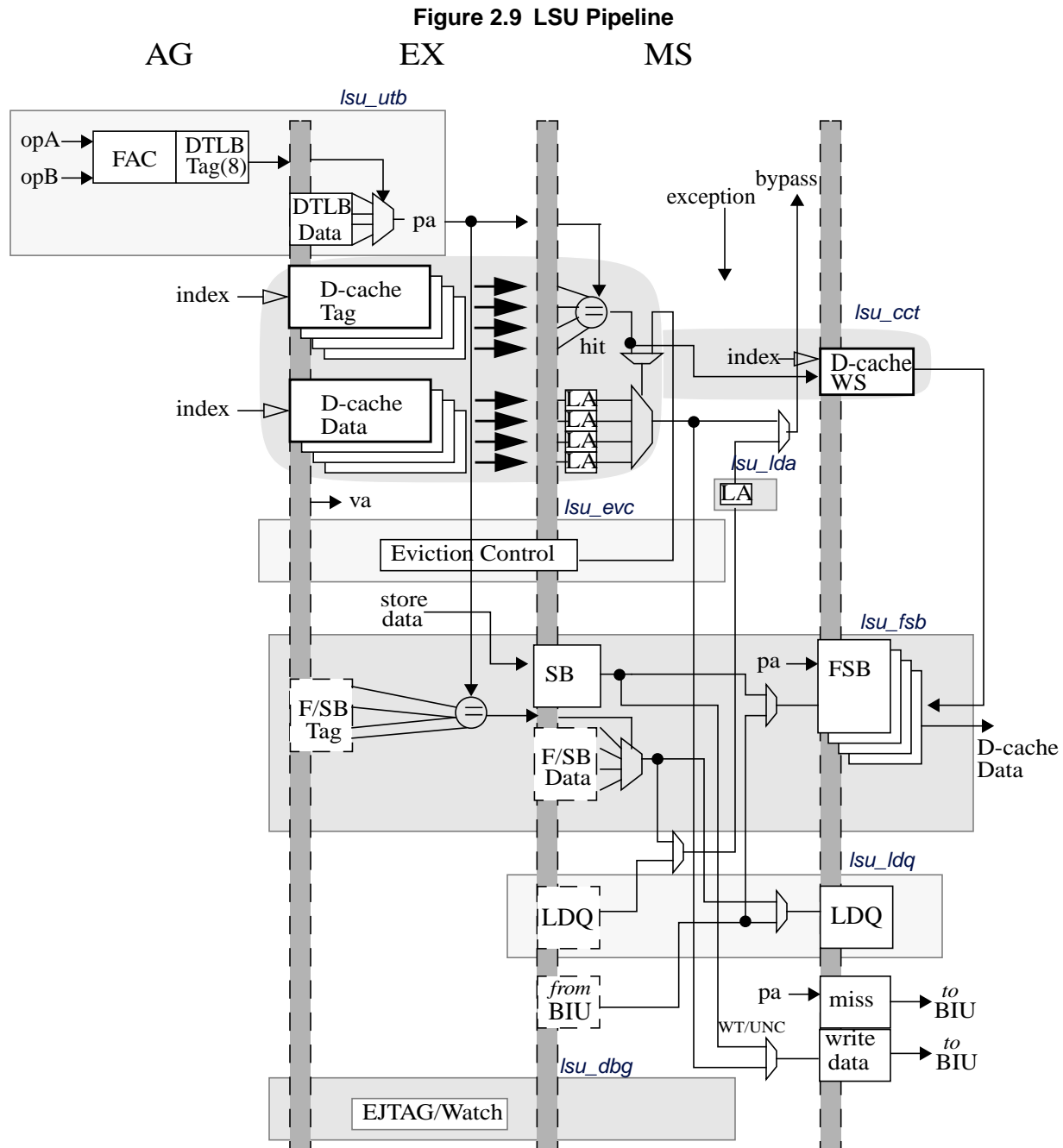
instruction it is extending are only recoded when they are in the fetch window together. Since a single fetch of 64bits can result in up to 4 MIPS16e instructions, in MIPS16e mode, the processor fetches every other cycle.

Table 2.1 Recode bandwidth

| First 16b | Second 16b | 32b Instns generated |
|-----------------|-----------------|----------------------|
| 16b instruction | 16b instruction | 2 |
| Extend | 16 instruction | 1 |
| 16b instruction | Extend/JAL(X) | 1 |
| JAL(X) | | 1 |

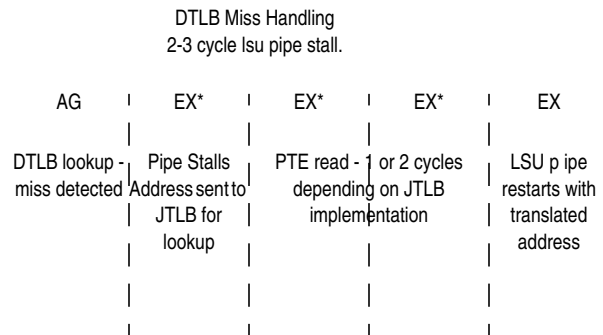
2.3 Load Store Unit

The Load Store Unit (LSU) is responsible for loads and stores. This primarily includes the data cache control logic.



2.3.1 DTLB

The data cache access begins in the AG stage. The ALU generates the virtual address in this stage. In parallel, the source operands are passed to the LSU and the 8-entry DTLB is accessed. If there is a miss in the DTLB, the LSU will stall and give the address to the BIU to lookup in the JTLB. If there is a hit in the JTLB, the page information will be returned to the LSU and the access will continue. Since it is only the LSU pipe that stalls on a DTLB miss, it is possible for other non load-store instructions to keep progressing down the ALU pipe.

Figure 2.10 DTLB Miss Timing

The DTLB will only store mappings either for 4K or 1M pages or subpages of a larger JTLB entry. A DTLB entry will also record the associated JTLB entry, so that for a JTLB write, the DTLB can invalidate its copy if present. The DTLB uses a pseudo-LRU replacement algorithm. If the Fixed Mapping MMU is used instead of a TLB, the address translation will be done in the EX stage, and there will never be a DTLB miss.

2.3.2 Data Cache Access

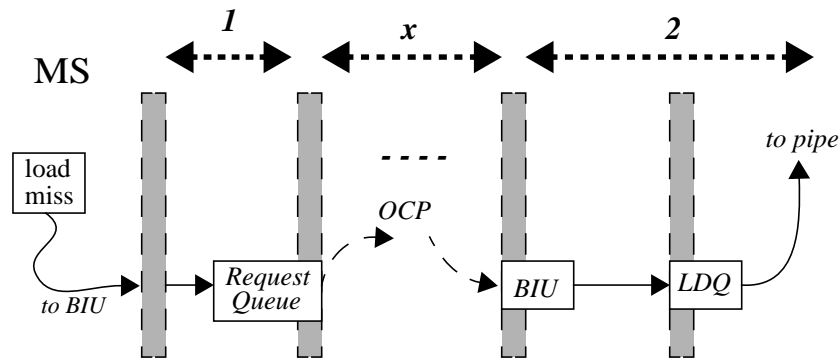
The data cache access is done during the EX stage. The tag and data arrays are accessed and the values are saved in flops for use in the MS stage. In parallel with the array lookup (in EX), the physical address is used to do an early tag compare on entries in the Fill Store Buffer (FSB) and Store Buffer (SB).

The SB is a single entry buffer that is used to stage store data into the other structures. It is fully bypass-able, allowing a load immediately after a store to the same address to execute without stalls. From the SB, the store data will move into the FSB if the store hits in the cache or it is an allocating miss. The store data is then written into the cache opportunistically.

During the MS stage, the data cache tags are compared to the physical address to determine whether a reference hit in the cache or not. If there is a hit, the way select (WS) array will be written to mark the most recently used way, and load data will be bypassed back to the ALU. On a cache miss, an FSB entry is allocated to hold the fill data as it returns from the BIU. The WS array is read and the replacement way is determined. If the line selected for replacement is dirty, an eviction will begin and the dirty data will be written back to memory. A load miss will also allocate an entry in the Load Queue (LDQ). This buffer is used to hold the aligned load data while it is being staged back into the ALU.

The core portion of a load miss is shown in [Figure 2.11](#). It takes one cycle to get from the LSU through the BIU and out onto the OCP bus. It takes at least 1 cycle for the data to be returned. Then 2 more cycles are required to get the data back to the ALU.

Figure 2.11 Cache Miss Timing



2.3.3 Outstanding misses

The 24K core features non-blocking D-cache misses. In the cases where the following instructions are not dependent on the load data, the core can continue executing instructions while the miss is being processed. The core can handle multiple outstanding misses.

- Up to 8 independent cache lines - this includes cache refills requested for loads, stores, and prefetches as well as single uncached load requests. Multiple cacheable requests to the same line can be merged. This limit is dependent on the number of Fill-Store Buffer (FSB) entries the core is configured with.
- Up to 9 load misses - Up to 9 separate loads can be outstanding. The loads can be to different cache lines or multiple loads can be to the same cache line. This limit is dependent on the number of Load Data Queue (LDQ) entries the core was built with.

2.3.4 Uncached Accesses

Uncached accesses are handled similarly to cached accesses. The cacheability of the reference is not known until the address translation has completed in the EX stage, so the cache access is performed anyway. On an uncached reference, a miss will be forced. Uncached loads will request the exact amount of data required and allocate an FSB and LDQ entry. Uncached loads are non-blocking just like cached misses. Uncached stores will be sent to the BIU.

To the LSU, uncached accelerated stores look the same as uncached stores. In the BIU, however, they are handled differently—the BIU will attempt to gather uncached accelerated stores and do a bursted write to improve bus efficiency.

2.4 MDU Pipeline

The autonomous multiply/divide unit (MDU) has a separate pipeline for multiply and divide operations. This pipeline operates in parallel with the integer unit (ALU) pipeline and does not stall when the ALU pipeline stalls. This allows multi-cycle MDU operations, such as a divide, to be partially masked by system stalls and/or other integer unit instructions.

The MDU consists of a 32x32 booth recoded multiplier array, separate carry-lookahead adders for multiply and divide, result/accumulation registers (*H1* and *LO*), multiply and divide state machines, and all necessary multiplexers and control logic.

The MDU supports execution of a multiply operation every clock cycle. Divide operations are implemented with a simple 1 bit per clock iterative algorithm with an early in detection of sign extension on the dividend (*rs*). An attempt to issue a subsequent MDU instruction which would access the *H/I* or *L/O* register before the divide completes causes a delay in starting the subsequent MDU instruction. Some concurrency is enabled by the separate adders for the multiply and divide data paths. The MDU instruction may start executing once the divide is ensured of writing to the *H/I* and *L/O* registers before the MDU instruction will access them. A MUL instruction, which does not access the *H/I* or *L/O* register, may start executing anytime relative to a previous divide instruction.

Table 2.2 lists the delays (number of cycles until a result is available) for multiply and divide instructions. The delays are listed in terms of pipeline clocks. In this table ‘delay’ refers to the number of cycles the pipeline must stall the second instruction to wait for the result of the first instruction.

Table 2.2 MDU Instruction Delays

| Size of Operand 1st Instruction ^[1] | Instruction Sequence | | Delay Clocks |
|---|---|---|-------------------|
| | 1st Instruction | 2nd Instruction | |
| 32 bit | MULT/MULTU, MADD/MADDU, or MSUB/MSUBU | MADD/MADDU, MSUB/MSUBU, or MFHI/MFLO | 0 |
| 32 bit | MUL | Integer operation ^[1] | 4 |
| 8 bit | DIVU | MFHI/MFLO | 7 |
| 16 bit | DIVU | MFHI/MFLO | 15 |
| 24 bit | DIVU | MFHI/MFLO | 23 |
| 32 bit | DIVU | MFHI/MFLO | 31 |
| 8 bit | DIV | MFHI/MFLO | 9 ^[2] |
| 16 bit | DIV | MFHI/MFLO | 17 ^[2] |
| 24 bit | DIV | MFHI/MFLO | 25 ^[2] |
| 32 bit | DIV | MFHI/MFLO | 33 ^[2] |
| any | MFHI/MFLO | Integer operation ^[1] | 4 |
| any | MTHI/MTLO | MADD/MADDU, MSUB/MSUBU | 1 |
| any | MTHI/MTLO | MFHI/MFLO | 0 |

[1] Integer Operation refers to any integer instruction that uses the result of a previous MDU operation.
 [2] If both operands are positive, then the two Sign Adjust stages are bypassed. Delay is then the same as for DIVU.

In Table 2.2 a delay of zero means that the first and second instructions can be issued back to back in the code without the MDU causing any stalls in the ALU pipeline. A delay of one means that if issued back to back, the ALU pipeline will be stalled for one cycle.

Table 2.3 Multiply Instruction (updating H/I/O) Repeat Rates

| Instruction Sequence | | Repeat Rate |
|--|---------------------------|----------------|
| 1st Instruction | 2nd Instruction | |
| MULT/MULTU, MADD/MADDU, MSUB/MSUBU | MADD/MADDU, MSUB/MSUBU | 1 |

The repeat rate of 1 for MULT/MULTU/MADD/MADDU/MSUB/MSUBU to MADD/MADDU/MSUB/MSUBU are achieved by feeding the result of the M3_{MDU} stage for the first instruction back into the M3_{MDU} stage for the second instruction.

Table 2.4 MUL Repeat Rates

| Instruction Sequence | | Repeat Rate |
|---|--------------------------|----------------------|
| 1st Instruction | 2nd Instruction | |
| MUL | MUL (no data dependency) | 1-3 ^[1,2] |
| <p>[1] There is no data dependency between first and second MUL. Otherwise, the repeat rate is the same as for MUL to integer operations in Figure 2.2</p> <p>[2] MULs can be issued at the maximum rate of 3 every 5 cycles. Three can be issued back to back, but a fourth one would stall.</p> | | |

2.4.1 Multiply Pipeline Stages

The multiply operation begins in B_{MDU} stage, which would be the EX stage in the integer pipeline. The booth recoding function occurs at this time. The multiply calculation requires three clocks and occurs in the M1_{MDU}, M2_{MDU}, and M3_{MDU} stages. The carry-lookahead-add (CLA) function occurs at the end of the M3_{MDU} stage. In the A_{MDU} stage, the result is selected from the multiply data path, *HI* register, and *LO* register to be returned to the ALU for the MFHI, MFLO, and MUL instructions. If the MDU instruction is not one of these, the result is selected to be written into the *HI/LO* registers instead. The result is ready to be read from the *HI/LO* registers in the W_{MDU} stage.

The following figures illustrate a multiply (accumulate) instruction and the interaction with the main integer pipeline. These figures are applicable to MUL, MULT, MULTU, MADD, MADDU, MSUB, and MSUBU instructions

Figure 2.12 Multiply Pipeline



Figure 2.13 Multiply With Dependency From ALU

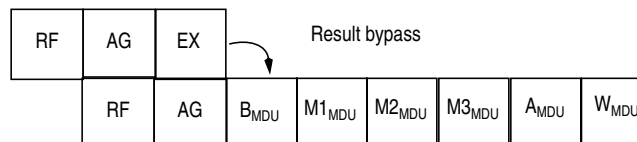
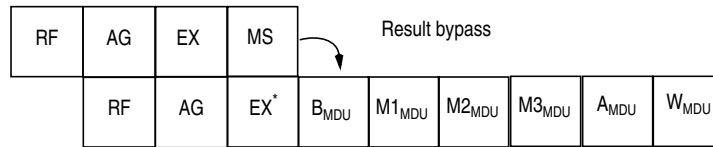
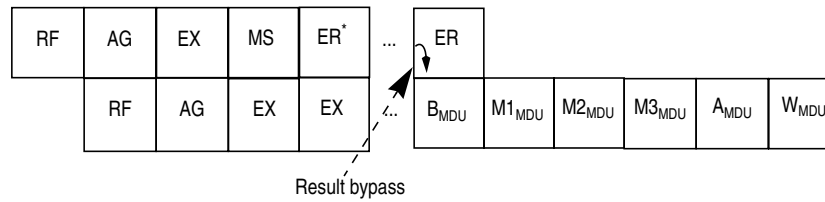


Figure 2.14 Multiply With Dependency From Load Hit



* - MUL enters EX stage but stalls because data is not ready

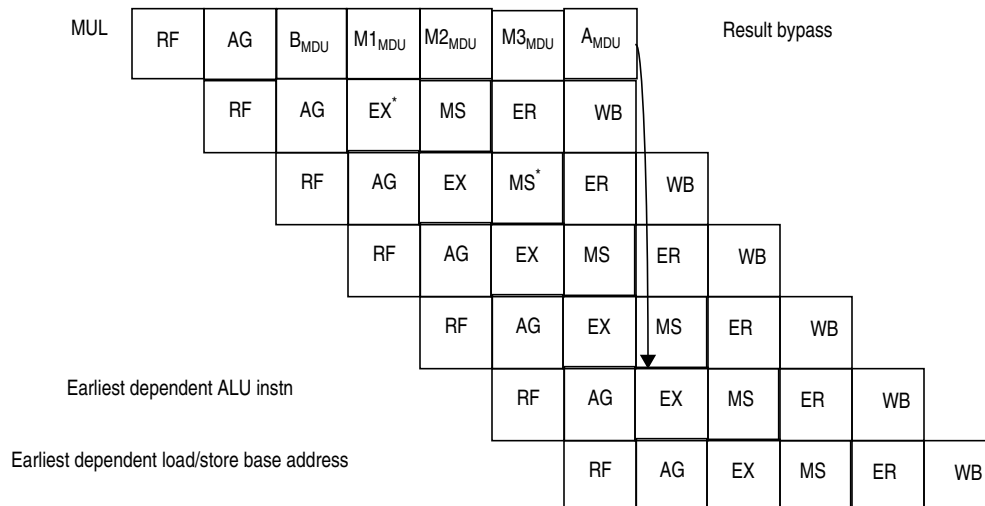
Figure 2.15 Multiply With Dependency From Load Miss



The following figure shows the results of the GPR targeted MUL instruction being bypassed to a later instruction. Independent instructions can execute while the multiply is happening. If a dependent instruction is found, it will stall until the result is available. When the MUL completes, it will arbitrate for access to the write port of the register file. If the integer pipe is busy with other instructions, the MDU pipeline will stall until the result can be written.

If the MUL target is being used as the base address for a load or store instruction, it needs to be bypassed by the AG stage, so one extra cycle will be required.

Figure 2.16 MUL Bypassing Result to Integer Instructions



2.4.2 Divide Operations

Divide operations are implemented using a simple non-restoring division algorithm. This algorithm works only for positive operands, hence the first cycle of the M_{MDU} stage is used to negate the rs operand (RS Adjust) if needed. Note that this cycle is spent even if the adjustment is not necessary. In cycle 2, the first add/subtract iteration is executed. In cycle 3 an early-in detection is performed. The adjusted rs operand is detected to be zero extended on the upper most 8, 16 or 24 bits. If this is the case the following 7, 15 or 23 cycles of the add/subtract iterations are skipped. During the next maximum 31 cycles (4-34), the remaining iterative add/subtract loop is executed.

The remainder adjust (Rem Adjust) cycle is required if the remainder was negative. Note that this cycle is spent even if the remainder was positive. A sign adjust is performed on the quotient and/or remainder if necessary. The sign adjust stages are skipped if both operands are positive.

Figure 2.17, Figure 2.18, Figure 2.19 and Figure 2.20 show the worst case latencies for 8, 16, 24 and 32 bit divide operations, respectively. The worst case repeat rate is either 14, 22, 30 or 38 cycles (two less if the *sign adjust* stage is skipped).

Figure 2.17 MDU Pipeline Flow During a 8-bit Divide (DIV) Operation

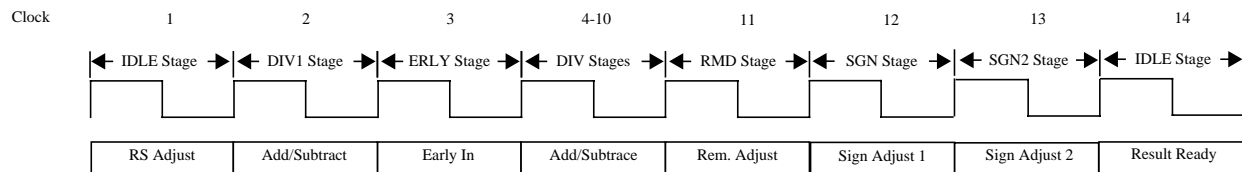


Figure 2.18 MDU Pipeline Flow During a 16-bit Divide (DIV) Operation

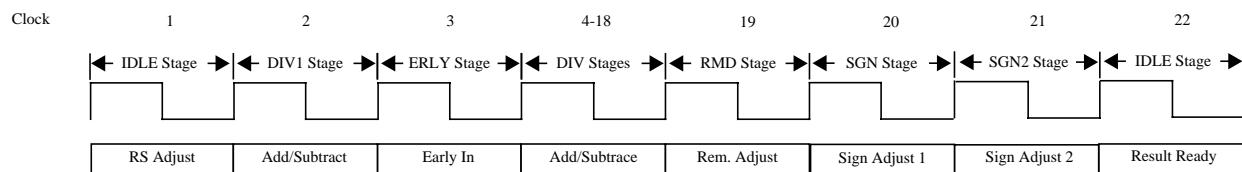


Figure 2.19 MDU Pipeline Flow During a 24-bit Divide (DIV) Operation

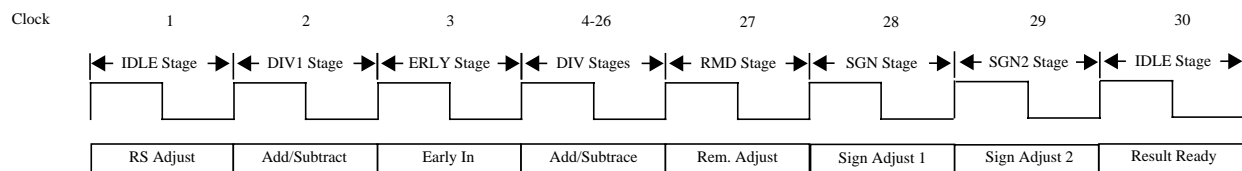
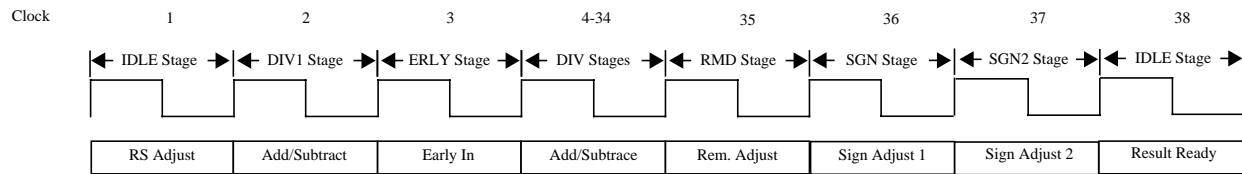


Figure 2.20 MDU Pipeline Flow During a 32-bit Divide (DIV) Operation

2.5 Skewed ALU

The 24K core has a skewed ALU. This is referring to the fact that the ALU is located in the EX stage instead of the AG stage. This allows the load to use delay to be two cycles, the same as it was in the shorter 4KE pipeline. Software optimized for that pipeline can run without incurring additional stalls. Of course, this does not come for free - an ALU instruction generating the base address for a load or store will have an additional cycle stall. Independent of the ALU location, pointer chasing loads (loads generating the base address for following loads) will see the full 3 cycles of cache access time.

This is shown in [Figure 2.21](#). The earliest an ALU consumer of load data can issue is two cycles after the load. The earliest a load/store consumer can issue is three cycles after the load.

The bypass of data from the ALU is shown in [Figure 2.22](#). For back to back ALU instructions, the result is bypassed from the EX stage to the AG stage. For an ALU bypassing to the base address register of a load or store, the bypassing is from the EX stage to the RF stage and the load cannot issue until two cycles after the ALU instruction. Note that the data register for a store is not used in the AG stage and a dependency there will look like the ALU to ALU bypass.

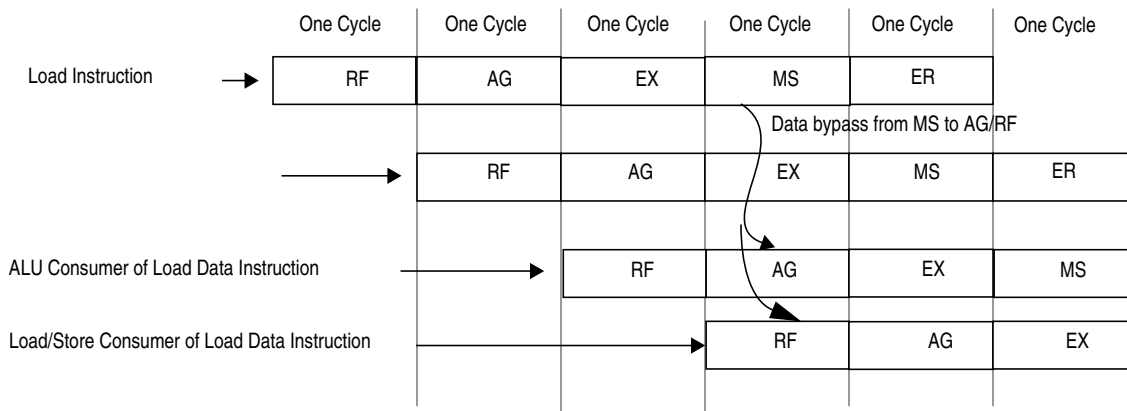
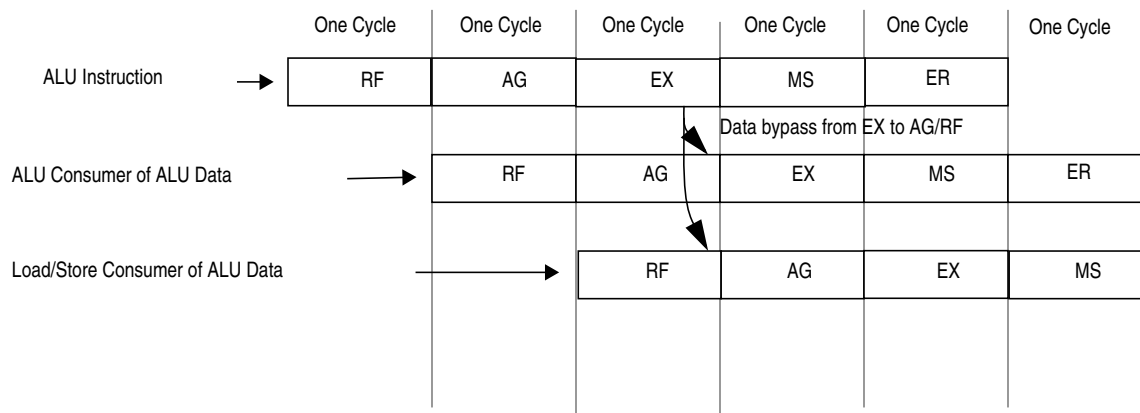
Figure 2.21 Load Data Bypass

Figure 2.22 ALU Data Bypass

2.6 Interlock Handling

Smooth pipeline flow is interrupted when cache misses occur or when data dependencies are detected. Interruptions handled entirely in hardware, such as cache misses, are referred to as *interlocks*. At each cycle, interlock conditions are checked for all active instructions.

Table 2.5 lists the types of pipeline interlocks for the 24K processor core.

Table 2.5 Pipeline Interlocks

| Interlock Type | Sources | Slip Stage |
|-------------------------------------|---|------------|
| GPR dependency - load/store address | Dest. register for any instruction in previous cycle | AG |
| | Dest. register for loads/MFCx/MDU instns in previous 2 cycles | |
| MDU busy | Previous MDU operation not completed | AG |
| GPR dependency | Dest. register for loads/MFCx/MDU instns in previous cycle | EX |
| LDQ full | Load in pipe while Load Queue is full | |
| Blocking load bubble | Blocking load immediately following another blocking load | |
| SYNC, I-Cache | Previous I-Cache not completed | |

Table 2.5 Pipeline Interlocks (Continued)

| Interlock Type | Sources | Slip Stage |
|----------------------------|--|------------|
| Destination GPR dependency | Outstanding GPR write to same register | MS |
| WBB full | Store/CACHE instn in pipe while Write-back Buffer is full | |
| SPRAM busy | SPRAM load/store in pipe while SPRAM is busy | |
| FSB flush | SYNC/CACHE/load/store instn requires Fill Store Buffer to be flushed | |
| DTLB miss | Load/Store address miss in microTLB | |
| CACHE | CACHE instn needs to re-access data cache | |
| L2 CACHE | Previous L2 CACHE not completed | |
| Blocking load miss | Load misses with non-blocking loads disabled | ER |

2.7 Instruction Interlocks

Most instructions can be issued at a rate of one per clock cycle. In order to adhere to the sequential programming model, the issue of an instruction must sometimes be delayed. This to ensure that the result of a prior instruction is available. [Table 2.6](#) details the instruction interactions that prevent an instruction from advancing in the processor pipeline.

Table 2.6 Instruction Interlocks

| Instruction Interlocks | | | |
|-----------------------------|---|--------------------------------|------------|
| First Instruction | Second Instruction | Issue Delay (in Clock Cycles) | Slip Stage |
| LB/LBU/LH/LHU/LL/LW/LWL/LWR | ALU Consumer of load data | 1 | EX stage |
| | Load/Store consumer for base address register | 2 | AG stage |
| MFC0 | ALU consumer of destination register | 2 | EX stage |
| | Load/store consumer for base address | 3 | AG stage |
| MULTx/MADDx/MSUBx | MFLO/MFHI | 0 | |
| MUL/MFHI/MFLO | ALU Consumer of target data | 4 | EX stage |
| | Load/Store consumer of target data for base address | 5 | AG stage |
| MULTx/MADDx/MSUBx | MULT/MUL/MADD/MSUB MTHI/MTLO/DIV | 0 | EX stage |
| DIV | MUL/MULTx/MADDx/MSUBx/MTHI/MTLO/MFHI/MFLO/DIV | See Figure 2.2 | EX stage |
| TLBWR/TLBWI | Load/Store/PREF/CACHE/COP0 op | 2 | EX stage |
| TLBR | | 1 | EX stage |

2.8 Hazards

In general, the 24K core ensures that instructions are executed following a fully sequential program model. Each instruction in the program sees the results of the previous instruction. There are some deviations to this model. These deviations are referred to as *hazards*.

Prior to Release 2 of the MIPS32® Architecture, hazards (primarily CP0 hazards) were relegated to implementation-dependent cycle-based solutions, primarily based on the SSNOP instruction. This has been an insufficient and error-prone practice that must be addressed with a firm compact between hardware and software. As such, new instructions have been added to Release 2 of the architecture which act as explicit barriers that eliminate hazards. To the extent that it was possible to do so, the new instructions have been added in such a way that they are backward-compatible with existing MIPS processors.

2.8.1 Types of Hazards

With one exception, all hazards were eliminated in Release 1 of the Architecture for unprivileged software. The exception occurs when unprivileged software writes a new instruction sequence and then wishes to jump to it. Such an operation remained a hazard, and is addressed by the capabilities of Release 2.

In privileged software, there are two different types of hazards: *execution hazards* and *instruction hazards*. Both are defined below.

2.8.1.1 Execution Hazards

Execution hazards are those created by the execution of one instruction, and seen by the execution of another instruction. These hazards should be resolved by executing an EHB instruction or an instruction hazard barrier (JR.HB, JALR.HB, or ERET) between the two instructions. [Table 2.7](#) lists execution hazards.

Table 2.7 Execution Hazards

| Producer | → | Consumer | Hazard On | Spacing (Instructions) |
|--------------|---|--|---|---------------------------|
| TLBWR, TLBWI | → | TLBP, TLBR | TLB entry | 2 |
| | | Load/store using new TLB entry | TLB entry | 3 |
| MTC0 | → | Load/store affected by new state | WatchHi WatchLo | 2 |
| MTC0 | → | MFC0 | any cp0 register | 2 |
| MTC0 | → | EI/DI | Status | 2 |
| MTC0 | → | RDHWR \$3 | Count | 2 |
| MTC0 | → | ERET | EPC DEPC ErrorEPC | 2 |
| MTC0 | → | ERET | Status | 2 |
| EI, DI | → | Interrupted instruction | Status _{IE} | 2 |
| MTC0 | → | Interrupted instruction | Status | 2 |
| MTC0 | → | User-defined instruction (only for Pro core) | Status _{ERL} Status _{EXL} | 4 |
| MTC0 | → | Interrupted Instruction | Cause _{IP} | 2 |

Table 2.7 Execution Hazards

| Producer | → | Consumer | Hazard On | Spacing (Instructions) |
|----------|---|---|--|---------------------------|
| TLBR | → | MFC0 | EntryHi, EntryLo0, EntryLo1, Page- Mask | 2 |
| TLBP | → | MFC0 | Index | 2 |
| MTC0 | → | TLBR TLBWI TLBWR | EntryHi | 2 |
| MTC0 | → | TLBP Load/store affected by new state | EntryHi _{ASID} | 2 |
| MTC0 | → | TLBWI TLBWR | EntryLo0 EntryLo1 | 2 |
| MTC0 | → | TLBWI TLBWR | Index | 2 |
| MTC0 | → | RDPGPR WRPGPR | SRSCtl _{PSS} | 1 |
| MTC0 | → | Instruction not seeing a Timer Interrupt | Compare update that clears Timer Interrupt | 4 ¹ |
| MTC0 | → | Load/Store affected by new state | EntryHi _{ASID} | 3 |
| MTC0 | → | Load/Store affected by new state | Status _{ERL} | 3 |
| MTC0 | → | Load/Store affected by new state | Debug _{LSNM} | 3 |
| MTC0 | → | Coprocessor instruction affected by new state | Status _{CU} | 4 |
| MTC0 | → | Coprocessor instruction affected by new state | Status _{FR} | 4 |
| MTC0 | → | CorExtend instruction affected by new state | Status _{CEE} | 3 |
| MTC0 | → | MFTR / MTTR | VpeControl _{TargTC} | 4 |
| MTC0 | → | Instruction affected by change | Any other CP0 register | 2 |

1. This is the minimum value. Actual value is system-dependent since it is a function of the sequential logic between the *SI_TimerInt* output and the external logic which feeds *SI_TimerInt* back into one of the *SI_Int* inputs, or a function of the method for handling *SI_TimerInt* in an external interrupt controller.

2.8.1.2 Instruction Hazards

Instruction hazards are those created by the execution of one instruction, and seen by the instruction fetch of another instruction. Table 2.8 lists instruction hazards. Because the fetch unit is decoupled from the execution unit, these hazards are rather large. The use of a hazard barrier instruction is highly recommended for reliable clearing of instruction hazards.

Table 2.8 Instruction Hazards

| Producer | → | Consumer | Hazard On | Spacing (Instructions) |
|--------------|---|---------------------------------------|-----------|---------------------------|
| TLBWR, TLBWI | → | Instruction fetch using new TLB entry | TLB entry | 10 |

Table 2.8 Instruction Hazards

| Producer | → | Consumer | Hazard On | Spacing (Instructions) |
|------------------------------------|---|---|-------------------------|-------------------------------|
| MTC0 | → | Instruction fetch seeing the new value including: 1 change to ERL followed by an instruction fetch from the useg segment and 2 change to ERL or EXL followed by a Watch exception | Status | 10 |
| MTC0 | → | Instruction fetch seeing the new value | EntryHi _{ASID} | 10 |
| MTC0 | → | Instruction fetch seeing the new value | WatchHi WatchLo | 10 |
| Instruction stream write via CACHE | → | Instruction fetch seeing the new instruction stream | Cache entries | 10 |
| Instruction stream write via store | → | Instruction fetch seeing the new instruction stream | Cache entries | System-dependent ¹ |

1. This value depends on how long it takes for the store value to propagate through the system.

2.8.2 Instruction Listing

Table 2.9 lists the instructions designed to eliminate hazards. See the document titled *MIPS32® Architecture for Programmers Volume II: The MIPS32 Instruction Set* (MD00084) for a more detailed description of these instructions.

Table 2.9 Hazard Instruction Listing

| Mnemonic | Function |
|----------|---|
| EHB | Clear execution hazard |
| ERET | Clears both execution and instruction hazards |
| JALR.HB | Clears both execution and instruction hazards |
| JR.HB | Clears both execution and instruction hazards |
| SYNCI | Synchronize caches after instruction stream write |

2.8.2.1 Instruction Encoding

The EHB instruction is encoded using a variant of the NOP/SSNOP encoding. This encoding was chosen for compatibility with the Release 1 SSNOP instruction, such that existing software may be modified to be compatible with both Release 1 and Release 2 implementations. See the EHB instruction description for additional information.

The JALR.HB and JR.HB instructions are encoding using bit 10 of the *hint* field of the JALR and JR instructions. These encodings were chosen for compatibility with existing MIPS implementations, including many which pre-date the MIPS32 architecture. Because a pipeline flush clears hazards on most early implementations, the JALR.HB or JR.HB instructions can be included in existing software for backward and forward compatibility. See the JALR.HB and JR.HB instructions for additional information.

The SYNCI instruction is encoded using a new encoding of the REGIMM opcode. This encoding was chosen because it causes a Reserved Instruction exception on all Release 1 implementations. As such, kernel software running on processors that don't implement Release 2 can emulate the function using the CACHE instruction. SYNCI must be used in conjunction with an instruction hazard barrier to ensure that the updated value is seen.

```
SYNCI    offset(base)
```

SYNC
JR.HB
NOP

2.8.3 Eliminating Hazards

The Spacing column shown in [Table 2.7](#) and [Table 2.8](#) indicates the number of unrelated instructions (such as NOPs or SSNOPs) that, prior to the capabilities of Release 2, would need to be placed between the producer and consumer of the hazard in order to ensure that the effects of the first instruction are seen by the second instruction. Entries in the table that are listed as 0 are traditional MIPS hazards which are not hazards on the 24K core.

With the hazard elimination instructions available in Release 2, the preferred method to eliminate hazards is to place one of the instructions listed in [Table 2.9](#) between the producer and consumer of the hazard. Execution hazards can be removed by using the EHB, JALR.HB, or JR.HB instructions. Instruction hazards can be removed by using the JALR.HB or JR.HB instructions, in conjunction with the SYNCI instruction.

Floating-Point Unit of the 24Kf™ Core

This chapter describes the MIPS64® Floating-Point Unit (FPU) included in the 24Kf core. This chapter contains the following sections:

- [Section 3.1 “Features Overview”](#)
- [Section 3.2 “Enabling the Floating-Point Coprocessor”](#)
- [Section 3.3 “Data Formats”](#)
- [Section 3.4 “Floating-Point General Registers”](#)
- [Section 3.5 “Floating-Point Control Registers”](#)
- [Section 3.6 “Instruction Overview”](#)
- [Section 3.7 “Exceptions”](#)
- [Section 3.8 “Pipeline and Performance”](#)

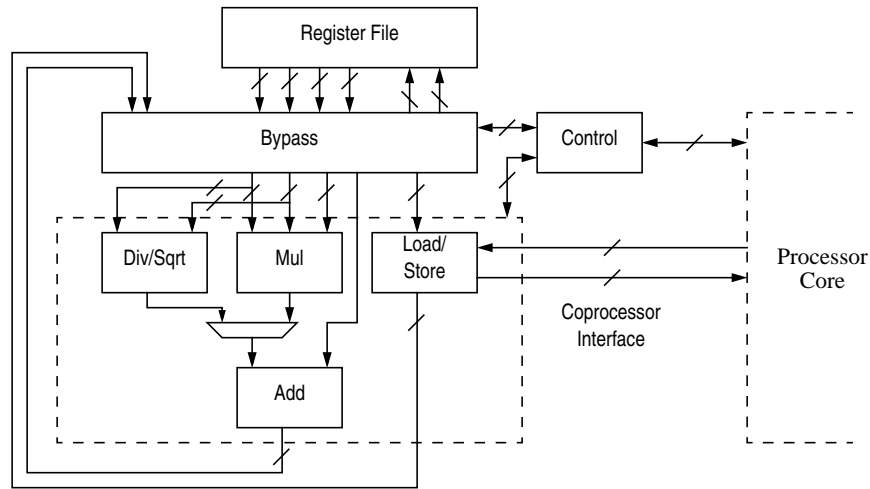
3.1 Features Overview

The FPU is provided via Coprocessor 1. Together with its dedicated system software, the FPU fully complies with the ANSI/IEEE Standard 754-1985, *IEEE Standard for Binary Floating-Point Arithmetic*. The MIPS architecture supports the recommendations of IEEE Standard 754, and the coprocessor implements a precise exception model. The key features of the FPU are listed below:

- Full 64-bit operation is implemented in both the register file and functional units.
- A 32-bit Floating-Point Control Register controls the operation of the FPU, and monitors condition codes and exception conditions.
- Like the main processor core, Coprocessor 1 is programmed and operated using a Load/Store instruction set. The processor core communicates with Coprocessor 1 using a dedicated coprocessor interface. The FPU functions as an autonomous unit. The hardware is completely interlocked such that, when writing software, the programmer does not have to worry about inserting delay slots after loads and between dependent instructions.
- Additional arithmetic operations not specified by IEEE Standard 754 (for example, reciprocal and reciprocal square root) are specified by the MIPS architecture and are implemented by the FPU. In order to achieve low latency counts, these instructions satisfy more relaxed precision requirements.
- The MIPS architecture further specifies compound multiply-add instructions. These instructions meet the IEEE accuracy specification where the result is numerically identical to an equivalent computation using multiply, add, subtract, or negate instructions.

Figure 3.1 depicts a block diagram of the FPU.

Figure 3.1 FPU Block Diagram



The MIPS architecture is designed such that a combination of hardware and software can be used to implement the architecture. The 24K core FPU can operate on numbers within a specific range (in general, the IEEE normalized numbers), but it relies on a software handler to operate on numbers not handled by the FPU hardware (in general, the IEEE denormalized numbers). Supported number ranges for different instructions are described later in this chapter. A fast Flush To Zero mode is provided to optimize performance for cases where IEEE denormalized operands and results are not supported by hardware. The fast Flush to Zero mode is enabled through the CP1 *FCSR* register; use of this mode is recommended for best performance.

3.1.1 IEEE Standard 754

The IEEE Standard 754-1985, *IEEE Standard for Binary Floating-Point Arithmetic*, is referred to in this chapter as “IEEE Standard 754”. IEEE Standard 754 defines the following:

- Floating-point data types
- The basic arithmetic, comparison, and conversion operations
- A computational model

IEEE Standard 754 does not define specific processing resources nor does it define an instruction set.

For more information about this standard, see the IEEE web page at <http://stdsbbs.ieee.org/>.

3.2 Enabling the Floating-Point Coprocessor

Coprocessor 1 is enabled through the CU1 bit in the CP0 *Status* register. When Coprocessor 1 is not enabled, any attempt to execute a floating-point instruction causes a Coprocessor Unusable exception.

3.3 Data Formats

The FPU provides both floating-point and fixed-point data types, which are described below:

- The single- and double-precision floating-point data types are those specified by IEEE Standard 754.
- The fixed-point types are signed integers provided by the MIPS architecture.

3.3.1 Floating-Point Formats

The FPU provides the following two floating-point formats:

- a 32-bit single-precision floating point (type S, shown in [Figure 3.2](#))
- a 64-bit double-precision floating point (type D, shown in [Figure 3.3](#))

The floating-point data types represent numeric values as well as the following special entities:

- Two infinities, $+\infty$ and $-\infty$
- Signaling non-numbers (SNaNs)
- Quiet non-numbers (QNaNs)
- Numbers of the form: $(-1)^s 2^E b_0.b_1 b_2..b_{p-1}$, where:
 - $s = 0$ or 1
 - $E =$ any integer between E_{\min} and E_{\max} , inclusive
 - $b_1 = 0$ or 1 (the high bit, b_0 , is to the left of the binary point)
 - p is the signed-magnitude precision

The single and double floating-point data types are composed of three fields—sign, exponent, fraction—whose sizes are listed in [Table 3.1](#).

Table 3.1 Parameters of Floating-Point Data Types

| Parameter | Single | Double |
|-------------------------------------|--------|--------|
| Bits of mantissa precision, p | 24 | 53 |
| Maximum exponent, E_{\max} | +127 | +1023 |
| Minimum exponent, E_{\min} | -126 | -1022 |
| Exponent <i>bias</i> | +127 | +1023 |
| Bits in exponent field, e | 8 | 11 |
| Representation of b_0 integer bit | hidden | hidden |
| Bits in fraction field, f | 23 | 52 |
| Total format width in bits | 32 | 64 |

Table 3.1 Parameters of Floating-Point Data Types (Continued)

| Parameter | Single | Double |
|---|------------------|-------------------|
| Magnitude of largest representable number | 3.4028234664e+38 | 1.7976931349e+308 |
| Magnitude of smallest normalized representable number | 1.1754943508e-38 | 2.2250738585e-308 |

Layouts of these three fields are shown in [Figure 3.2](#) and [Figure 3.3](#) below. The fields are:

- 1-bit sign, s
- Biased exponent, $e = E + bias$
- Binary fraction, $f = .b_1 b_2 \dots b_{p-1}$ (the b_0 bit is *hidden*; it is not recorded)

Figure 3.2 Single-Precision Floating-Point Format (S)

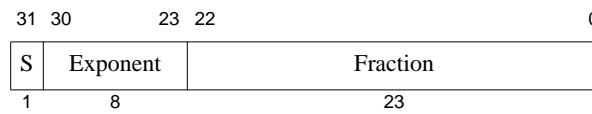
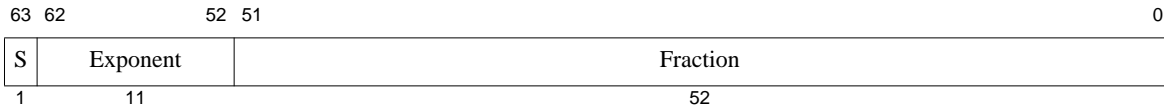


Figure 3.3 Double-Precision Floating-Point Format (D)



Values are encoded in the specified format using the unbiased exponent, fraction, and sign values listed in [Table 3.2](#). The high-order bit of the Fraction field, identified as b_1 , is also important for NaNs.

Table 3.2 Value of Single or Double Floating-Point Data Type Encoding

| Unbiased E | f | s | b_1 | Value V | Type of Value | Typical Single Bit Pattern ¹ | Typical Double Bit Pattern ¹ |
|------------------------|----------|---|-------|-----------------------|------------------------------|---|---|
| $E_{max} + 1$ | $\neq 0$ | | 1 | SNaN | Signaling NaN | 0x7fffffff | 0x7fffffff ffffffff |
| | | | 0 | QNaN | Quiet NaN | 0x7fbfffff | 0x7fff7ffff ffffffff |
| $E_{max} + 1$ | 0 | 1 | | $-\infty$ | Minus infinity | 0xff800000 | 0xffff0000 00000000 |
| | | 0 | | $+\infty$ | Plus infinity | 0x7f800000 | 0x7ff00000 00000000 |
| E_{max} to E_{min} | | 1 | | $-(2^E)(1.f)$ | Negative normalized number | 0x80800000 through 0xff7fffff | 0x80100000 00000000 through 0xffefffff ffffffff |
| | | 0 | | $+(2^E)(1.f)$ | Positive normalized number | 0x00800000 through 0x7f7fffff | 0x00100000 00000000 through 0x7fefffff ffffffff |
| $E_{min} - 1$ | $\neq 0$ | 1 | | $-(2^{E_{min}})(0.f)$ | Negative denormalized number | 0x807fffff | 0x800fffff ffffffff |
| | | 0 | | $+(2^{E_{min}})(0.f)$ | Positive denormalized number | 0x007fffff | 0x000fffff ffffffff |
| $E_{min} - 1$ | 0 | 1 | | -0 | Negative zero | 0x80000000 | 0x80000000 00000000 |
| | | 0 | | +0 | positive zero | 0x00000000 | 0x00000000 00000000 |

1. The “Typical” nature of the bit patterns for the NaN and denormalized values reflects the fact that the sign might have either value (NaN) and that the fraction field might have any non-zero value (both). As such, the bit patterns shown are one value in a class of potential values that represent these special values.

3.3.1.1 Normalized and Denormalized Numbers

For single and double data types, each representable nonzero numerical value has just one encoding; numbers are kept in normalized form. The high-order bit of the p-bit mantissa, which lies to the left of the binary point, is “hidden,” and not recorded in the *Fraction* field. The encoding rules permit the value of this bit to be determined by looking at the value of the exponent. When the unbiased exponent is in the range E_{min} to E_{max} , inclusive, the number is normalized and the hidden bit must be 1. If the numeric value cannot be normalized because the exponent would be less than E_{min} , then the representation is denormalized, the encoded number has an exponent of $E_{min} - 1$, and the hidden bit has the value 0. Plus and minus zero are special cases that are not regarded as denormalized values.

3.3.1.2 Reserved Operand Values—Infinity and NaN

A floating-point operation can signal IEEE exception conditions, such as those caused by uninitialized variables, violations of mathematical rules, or results that cannot be represented. If a program does not trap IEEE exception conditions, a computation that encounters any of these conditions proceeds without trapping but generates a result indicating that an exceptional condition arose during the computation. To permit this case, each floating-point format defines representations (listed in [Table 3.2](#)) for plus infinity ($+\infty$), minus infinity ($-\infty$), quiet non-numbers (QNaN), and signaling non-numbers (SNaN).

3.3.1.3 Infinity and Beyond

Infinity represents a number with magnitude too large to be represented in the given format; it represents a magnitude overflow during a computation. A correctly signed ∞ is generated as the default result in division by zero operations and some cases of overflow as described in [Section 3.7.2 “Exception Conditions”](#).

Once created as a default result, ∞ can become an operand in a subsequent operation. The infinities are interpreted such that $-\infty < (\text{every finite number}) < +\infty$. Arithmetic with ∞ is the limiting case of real arithmetic with operands of arbitrarily large magnitude, when such limits exist. In these cases, arithmetic on ∞ is regarded as exact, and exception conditions do not arise. The out-of-range indication represented by ∞ is propagated through subsequent computations. For some cases, there is no meaningful limiting case in real arithmetic for operands of ∞ . These cases raise the Invalid Operation exception condition as described in [Section 3.7.2.1 “Invalid Operation Exception”](#).

3.3.1.4 Signalling Non-Number (SNaN)

SNaN operands cause an Invalid Operation exception for arithmetic operations. SNaNs are useful values to put in uninitialized variables. An SNaN is never produced as a result value.

IEEE Standard 754 states that “Whether copying a signaling NaN without a change of format signals the Invalid Operation exception is the implementor’s option.” The MIPS architecture makes the formatted operand move instructions (MOV.fmt, MOVT.fmt, MOVF.fmt, MOVN.fmt, MOVZ.fmt) non-arithmetic; they do not signal IEEE 754 exceptions.

3.3.1.5 Quiet Non-Number (QNaN)

QNaNs provide retrospective diagnostic information inherited from invalid or unavailable data and results. Propagation of the diagnostic information requires information contained in a QNaN to be preserved through arithmetic operations and floating-point format conversions.

QNaN operands do not cause arithmetic operations to signal an exception. When a floating-point result is to be delivered, a QNaN operand causes an arithmetic operation to supply a QNaN result. When possible, this QNaN result is one¹ of the operand QNaN values. QNaNs do have effects similar to SNaNs on operations that do not deliver a floating-point result—specifically, comparisons. (For more information, see the detailed description of the floating-point compare instruction, C.cond.fmt.).

When certain invalid operations not involving QNaN operands are performed but do not trap (because the trap is not enabled), a new QNaN value is created. Table 3.3 shows the QNaN value generated when no input operand QNaN value can be copied. The values listed for the fixed-point formats are the values supplied to satisfy IEEE Standard 754 when a QNaN or infinite floating-point value is converted to fixed point. There is no other feature of the architecture that detects or makes use of these “integer QNaN” values.

Table 3.3 Value Supplied When a New Quiet NaN is Created

| Format | New QNaN value |
|-----------------------|-----------------------|
| Single floating point | 0x7fbf ffff |
| Double floating point | 0x7ff7 ffff ffff ffff |
| Word fixed point | 0x7fff ffff |
| Longword fixed point | 0x7fff ffff ffff ffff |

3.3.2 Fixed-Point Formats

The FPU provides two fixed-point data types:

- a 32-bit Word fixed point (type W), shown in Figure 3.4
- a 64-bit Longword fixed point (type L), shown in Figure 3.5

The fixed-point values are held in 2’s complement format, which is used for signed integers in the CPU. Unsigned fixed-point data types are not provided by the architecture; application software can synthesize computations for unsigned integers from the existing instructions and data types.

Figure 3.4 Word Fixed-Point Format (W)

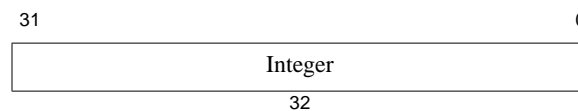
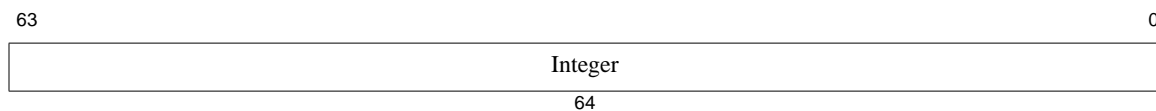


Figure 3.5 Longword Fixed-Point Format (L)



1. In case of one or more QNaN operands, a QNaN is propagated from one of the operands according to the following priority:
1: fs, 2: ft, 3: fr.

3.4 Floating-Point General Registers

This section describes the organization and use of the Floating-Point general Registers (FPRs). The FPU is a 64b FPU, but a 32b register mode for backwards compatibility is also supported. The FR bit in the CP0 *Status* register determines which mode is selected:

- When the FR bit is a 1, the 64b register model is selected, which defines 32 64-bit registers with all formats supported in a register.
- When the FR bit is a 0, the 32b register model is selected, which defines 32 32-bit registers with D-format values stored in even-odd pairs of registers; thus the register file can also be viewed as having 16 64-bit registers.

These registers transfer binary data between the FPU and the system, and are also used to hold formatted FPU operands and values.

3.4.1 FPRs and Formatted Operand Layout

FPU instructions that operate on formatted operand values specify the Floating-Point Register (FPR) that holds the value. Operands that are only 32 bits wide (*W* and *S* formats) use only half the space in an FPR.

Figure 3.6 and Figure 3.7 show the FPR organization and the way that operand data is stored in them.

Figure 3.6 Single Floating-Point or Word Fixed-Point Operand in an FPR

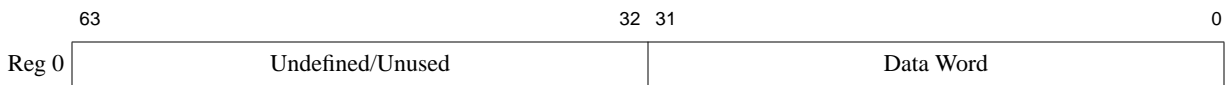
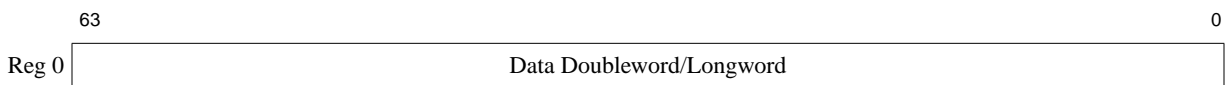


Figure 3.7 Double Floating-Point or Longword Fixed-Point Operand in an FPR



3.4.2 Formats of Values Used in FP Registers

Unlike the CPU, the FPU neither interprets the binary encoding of source operands nor produces a binary encoding of results for every operation. The value held in a floating-point operand register (FPR) has a format, or type, and it can be used only by instructions that operate on that format. The format of a value is either *uninterpreted*, *unknown*, or one of the valid numeric formats: *single* or *double* floating point, and *word* or *long* fixed point.

The value in an FPR is always set when a value is written to the register as follows:

- When a data transfer instruction writes binary data into an FPR (a load), the FPR receives a binary value that is *uninterpreted*.
- A computational or FP register move instruction that produces a result of type *fmt* puts a value of type *fmt* into the result register.

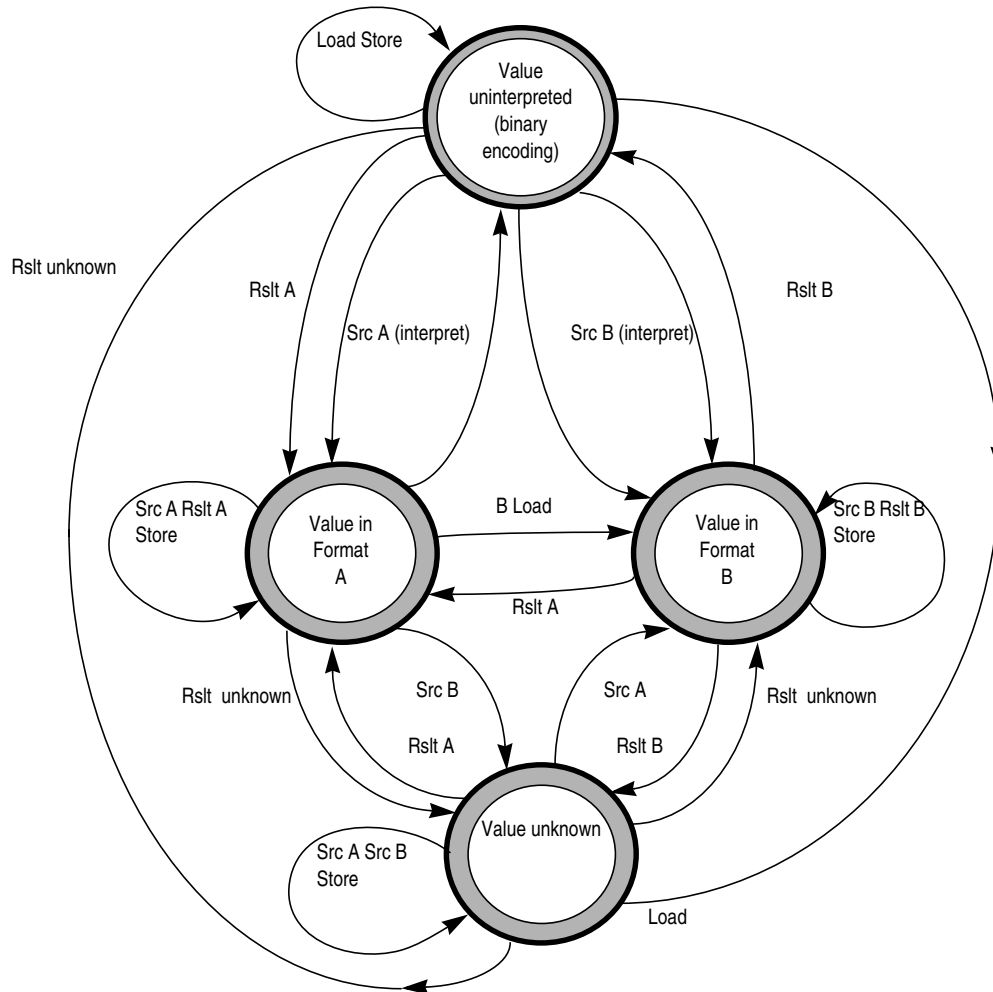
When an FPR with an *uninterpreted* value is used as a source operand by an instruction that requires a value of format *fmt*, the binary contents are interpreted as an encoded value in format *fmt*, and the value in the FPR changes to a value of format *fmt*. The binary contents cannot be reinterpreted in a different format.

If an FPR contains a value of format *fmt*, a computational instruction must not use the FPR as a source operand of a different format. If this case occurs, the value in the register becomes *unknown*, and the result of the instruction is also a value that is *unknown*. Using an FPR containing an *unknown* value as a source operand produces a result that has an *unknown* value.

The format of the value in the FPR is unchanged when it is read by a data transfer instruction (a store). A data transfer instruction produces a binary encoding of the value contained in the FPR. If the value in the FPR is *unknown*, the encoded binary value produced by the operation is not defined.

The state diagram in [Figure 3.8](#) illustrates the manner in which the formatted value in an FPR is set and changed.

Figure 3.8 Effect of FPU Operations on the Format of Values Held in FPRs



A, B: Example formats
 Load: Destination of LWC1, LDC1, or MTC1 instructions.
 Store: Source operand of SWC1, SDC1, or MFC1 instructions.
 Src fmt: Source operand of computational instruction expecting format "fmt."
 Rslt fmt: Result of computational instruction producing value of format "fmt."

3.4.3 Binary Data Transfers (32-Bit and 64-Bit)

The data transfer instructions move words and doublewords between the FPU FPRs and the remainder of the system. The operations of the word and doubleword load and move-to instructions are shown in Figure 3.9 and Figure 3.10, respectively.

The store and move-from instructions operate in reverse, reading data from the location that the corresponding load or move-to instruction had written.

Figure 3.9 FPU Word Load and Move-to Operations

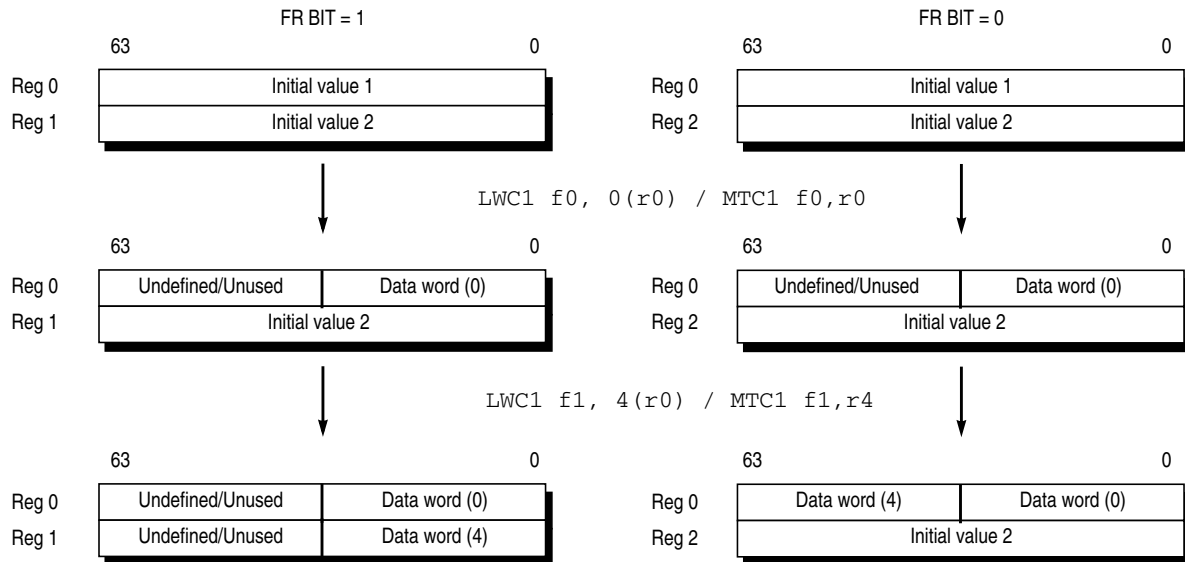
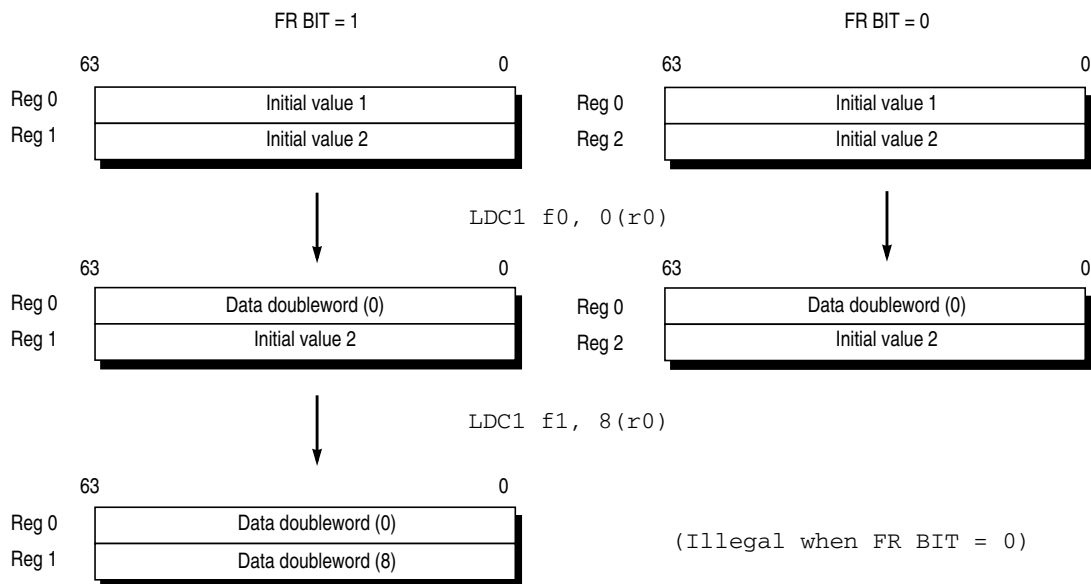


Figure 3.10 FPU Doubleword Load and Move-to Operations



3.5 Floating-Point Control Registers

The FPU Control Registers (FCRs) identify and control the FPU. The five FPU control registers are 32 bits wide: *FIR*, *FCCR*, *FEXR*, *FENR*, *FCSR*. Three of these registers, *FCCR*, *FEXR*, and *FENR*, select subsets of the floating-point Control/Status register, the *FCSR*. These registers are also denoted Coprocessor 1 (CP1) control registers.

CP1 control registers are summarized in [Table 3.4](#) and are described individually in the following subsections of this chapter. Each register's description includes the read/write properties and the reset state of each field.

Table 3.4 Coprocessor 1 Register Summary

| Register Number | Register Name | Function |
|-----------------|---------------|---|
| 0 | FIR | Floating-Point Implementation register. Contains information that identifies the FPU. |
| 25 | FCCR | Floating-Point Condition Codes register. |
| 26 | FEXR | Floating-Point Exceptions register. |
| 28 | FENR | Floating-Point Enables register. |
| 31 | FCSR | Floating-Point Control and Status register. |

[Table 3.5](#) defines the notation used for the read/write properties of the register bit fields.

Table 3.5 Read/Write Properties

| Read/Write Notation | Hardware Interpretation | Software Interpretation |
|---------------------|---|--|
| R/W | All bits in this field are readable and writable by software and potentially by hardware. Hardware updates of this field are visible by software reads. Software updates of this field are visible by hardware reads. If the reset state of this field is “Undefined,” either software or hardware must initialize the value before the first read returns a predictable value. This definition should not be confused with the formal definition of UNDEFINED behavior. | |
| R | This field is either static or is updated only by hardware. If the Reset State of this field is either “0” or “Pre-set”, hardware initializes this field to zero or to the appropriate state, respectively, on powerup. If the Reset State of this field is “Undefined”, hardware updates this field only under those conditions specified in the description of the field. | A field to which the value written by software is ignored by hardware. Software may write any value to this field without affecting hardware behavior. Software reads of this field return the last value updated by hardware. If the Reset State of this field is “Undefined,” software reads of this field result in an UNPREDICTABLE value except after a hardware update done under the conditions specified in the description of the field. |
| 0 | Hardware does not update this field. Hardware can assume a zero value. | The value software writes to this field must be zero. Software writes of non-zero values to this field might result in UNDEFINED behavior of the hardware. Software reads of this field return zero as long as all previous software writes are zero. If the Reset State of this field is “Undefined,” software must write this field with zero before it is guaranteed to read as zero. |

3.5.1 Floating-Point Implementation Register (FIR, CP1 Control Register 0)

The Floating-Point Implementation Register (*FIR*) is a 32-bit read-only register that contains information identifying the capabilities of the FPU, the Floating-Point processor identification, and the revision level of the FPU. [Figure 3.11](#) shows the format of the *FIR*; [Table 3.6](#) describes the *FIR* bit fields.

Figure 3.11 FIR Format

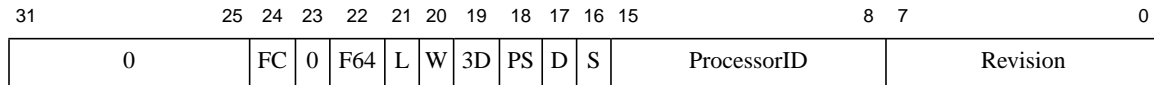


Table 3.6 FIR Bit Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| FC | 24 | Indicates that full convert ranges are implemented: 0: Full convert ranges not implemented 1: Full convert ranges implemented This bit is always 1 to indicate that full convert ranges are implemented. This means that all numbers can be converted to another type by the FPU (If FS bit in FCSR is not set Unimplemented Operation exception can still happen on denormal operands though). | R | 1 |
| F64 | 22 | Indicates that this is a 64-bit FPU: 0: Not a 64-bit FPU 1: A 64-bit FPU. This bit is always 1 to indicate that this is a 64-bit FPU. | R | 1 |
| L | 21 | Indicates that the long fixed point (L) data type and instructions are implemented: 0: Long type not implemented 1: Long implemented This bit is always 1 to indicate that long fixed point data types are implemented. | R | 1 |
| W | 20 | Indicates that the word fixed point (W) data type and instructions are implemented: 0: Word type not implemented 1: Word implemented This bit is always 1 to indicate that word fixed point data types are implemented. | R | 1 |
| 3D | 19 | Indicates that the MIPS-3D ASE is implemented: 0: MIPS-3D not implemented 1: MIPS-3D implemented This bit is always 0 to indicate that MIPS-3D is not implemented. | R | 0 |
| PS | 18 | Indicates that the paired-single (PS) floating-point data type and instructions are implemented: 0: PS floating-point not implemented 1: PS floating-point implemented This bit is always 0 to indicate that paired-single floating-point data types are not implemented. | R | 0 |

Table 3.6 FIR Bit Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------------|-----------|---|--------------|-------------|
| Name | Bits | | | |
| D | 17 | Indicates that the double-precision (D) floating-point data type and instructions are implemented: 0: D floating-point not implemented 1: D floating-point implemented This bit is always 1 to indicate that double-precision floating-point data types are implemented. | R | 1 |
| S | 16 | Indicates that the single-precision (S) floating-point data type and instructions are implemented: 0: S floating-point not implemented 1: S floating-point implemented This bit is always 1 to indicate that single-precision floating-point data types are implemented. | R | 1 |
| Processor ID | 15:8 | Identifies the floating-point processor. This value matches the corresponding field of the CP0 PRId register. | R | 0x93 |
| Revision | 7:0 | Specifies the revision number of the FPU. This field allows software to distinguish between one revision and another of the same floating-point processor type. This value matches the corresponding field of the CP0 PRId register. | R | Hardwired |
| 0 | 31:25, 23 | These bits must be written as zeros; they return zeros on reads. | 0 | 0 |

3.5.2 Floating-Point Condition Codes Register (FCCR, CP1 Control Register 25)

The Floating-Point Condition Codes Register (*FCCR*) is an alternative way to read and write the floating-point condition code values that also appear in the *FCSR*. Unlike the *FCSR*, all eight FCC bits are contiguous in the *FCCR*.

[Figure 3.12](#) shows the format of the *FCCR*; [Table 3.7](#) describes the *FCCR* bit fields.

Figure 3.12 FCCR Format

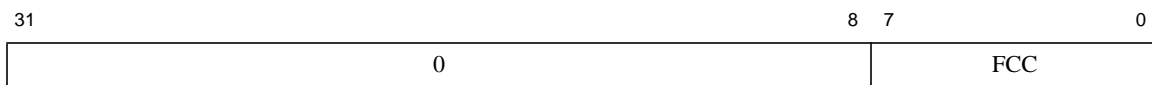


Table 3.7 FCCR Bit Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| FCC | 7:0 | Floating-point condition code. Refer to the description of this field in Section 3.5.5 “Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)” . | R/W | Undefined |
| 0 | 31:8 | These bits must be written as zeros; they return zeros on reads. | 0 | 0 |

3.5.3 Floating-Point Exceptions Register (FEXR, CP1 Control Register 26)

The Floating-Point Exceptions Register (*FEXR*) is an alternative way to read and write the Cause and Flags fields that also appear in the *FCSR*. [Figure 3.13](#) shows the format of the *FEXR*; [Table 3.8](#) describes the *FEXR* bit fields.

Figure 3.13 FEXR Format

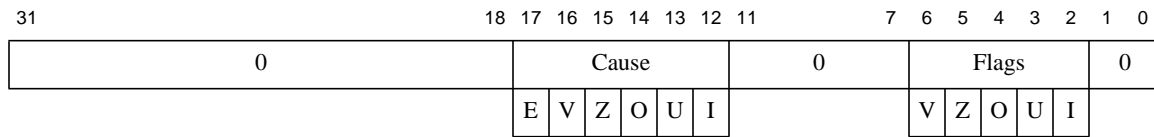


Table 3.8 FEXR Bit Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------------------|---|--------------|-------------|
| Name | Bits | | | |
| Cause | 17:12 | Cause bits. Refer to the description of this field in Section 3.5.5, "Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)" . | R/W | Undefined |
| Flags | 6:2 | Flag bits. Refer to the description of this field in Section 3.5.5 "Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)" . | R/W | Undefined |
| 0 | 31:18, 11:7, 1:0 | These bits must be written as zeros; they return zeros on reads. | 0 | 0 |

3.5.4 Floating-Point Enables Register (FENR, CP1 Control Register 28)

The Floating-Point Enables Register (*FENR*) is an alternative way to read and write the Enables, FS, and RM fields that also appear in the *FCSR*. [Figure 3.14](#) shows the format of the *FENR*; [Table 3.9](#) describes the *FENR* bit fields.

Figure 3.14 FENR Format

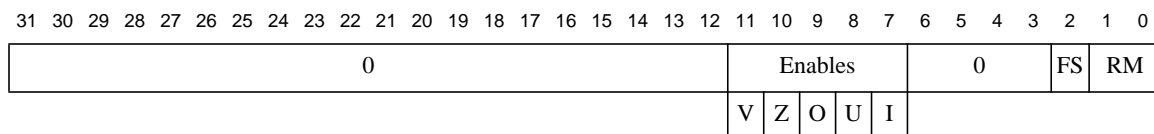


Table 3.9 FENR Bit Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|------|---|--------------|-------------|
| Name | Bits | | | |
| Enables | 11:7 | Enable bits. Refer to the description of this field in Section 3.5.5 "Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)" . | R/W | Undefined |

Table 3.9 FENR Bit Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------------|--|--------------|-------------|
| Name | Bits | | | |
| FS | 2 | Flush to Zero bit. Refer to the description of this field in Section 3.5.5, "Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)" . | R/W | Undefined |
| RM | 1:0 | Rounding mode. Refer to the description of this field in Section 3.5.5, "Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)" . | R/W | Undefined |
| 0 | 31:12, 6:3 | These bits must be written as zeros; they return zeros on reads. | 0 | 0 |

3.5.5 Floating-Point Control and Status Register (FCSR, CP1 Control Register 31)

The 32-bit Floating-Point Control and Status Register (*FCSR*) controls the operation of the FPU and shows the following status information:

- selects the default rounding mode for FPU arithmetic operations
- selectively enables traps of FPU exception conditions
- controls some denormalized number handling options
- reports any IEEE exceptions that arose during the most recently executed instruction
- reports any IEEE exceptions that cumulatively arose in completed instructions
- indicates the condition code result of FP compare instructions

Access to the *FCSR* is not privileged; it can be read or written by any program that has access to the FPU (via the coprocessor enables in the *Status* register). [Figure 3.15](#) shows the format of the *FCSR*; [Table 3.10](#) describes the *FCSR* bit fields.

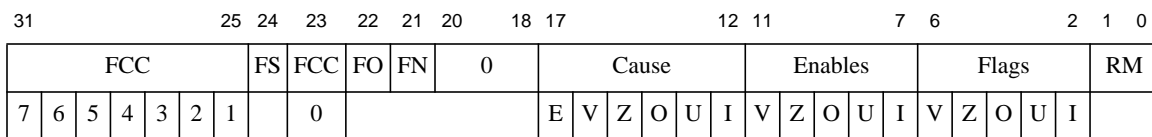
Figure 3.15 FCSR Format

Table 3.10 FCSR Bit Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|-----------|---|--------------|-------------|
| Name | Bit | | | |
| FCC | 31:25, 23 | Floating-point condition codes. These bits record the result of floating-point compares and are tested for floating-point conditional branches and conditional moves. The FCC bit to use is specified in the compare, branch, or conditional move instruction. For backward compatibility with previous MIPS ISAs, the FCC bits are separated into two non-contiguous fields. | R/W | Undefined |
| FS | 24 | Flush to Zero (FS). Refer to Section 3.5.6 “Operation of the FS/FO/FN Bits” for more details on this bit. | R/W | Undefined |
| FO | 22 | Flush Override (FO). Refer to Section 3.5.6 “Operation of the FS/FO/FN Bits” for more details on this bit. | R/W | Undefined |
| FN | 21 | Flush to Nearest (FN). Refer to Section 3.5.6 “Operation of the FS/FO/FN Bits” for more details on this bit. | R/W | Undefined |
| Cause | 17:12 | Cause bits. These bits indicate the exception conditions that arise during execution of an FPU arithmetic instruction. A bit is set to 1 when the corresponding exception condition arises during the execution of an instruction; otherwise, it is cleared to 0. By reading the registers, the exception condition caused by the preceding FPU arithmetic instruction can be determined. Refer to Table 3.11 for the meaning of each cause bit. | R/W | Undefined |
| Enables | 11:7 | Enable bits. These bits control whether or not a trap is taken when an IEEE exception condition occurs for any of the five conditions. The trap occurs when both an enable bit and its corresponding cause bit are set either during an FPU arithmetic operation or by moving a value to the <i>FCSR</i> or one of its alternative representations. Note that Cause bit E (CauseE) has no corresponding enable bit; the MIPS architecture defines non-IEEE Unimplemented Operation exceptions as always enabled. Refer to Table 3.11 for the meaning of each enable bit. | R/W | Undefined |
| Flags | 6:2 | Flag bits. This field shows any exception conditions that have occurred for completed instructions since the flag was last reset by software. When an FPU arithmetic operation raises an IEEE exception condition that does not result in a Floating-Point Exception (the enable bit was off), the corresponding bit(s) in the Flags field are set, while the others remain unchanged. Arithmetic operations that result in a Floating-Point Exception (the enable bit was on) do not update the Flags field. Hardware never resets this field; software must explicitly reset this field. Refer to Table 3.11 for the meaning of each flag bit. | R/W | Undefined |

Table 3.10 FCSR Bit Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|-------|---|--------------|-------------|
| Name | Bit | | | |
| RM | 1:0 | Rounding mode. This field indicates the rounding mode used for most floating-point operations (some operations use a specific rounding mode). Refer to Table 3.12 for the encoding of this field. | R/W | Undefined |
| 0 | 20:18 | These bits must be written as zeros; they return zeros on reads. | 0 | 0 |

Table 3.11 Cause, Enables, and Flags Definitions

| Bit Name | Bit Meaning |
|----------|--|
| E | Unimplemented Operation (this bit exists only in the Cause field). |
| V | Invalid Operations |
| Z | Divide by Zero |
| O | Overflow |
| U | Underflow |
| I | Inexact |

Table 3.12 Rounding Mode Definitions

| RM Field Encoding | Meaning |
|-------------------|---|
| 0 | RN - Round to Nearest Rounds the result to the nearest representable value. When two representable values are equally near, the result is rounded to the value whose least significant bit is zero (even). |
| 1 | RZ - Round Toward Zero Rounds the result to the value closest to but not greater in magnitude than the result. |
| 2 | RP - Round Towards Plus Infinity Rounds the result to the value closest to but not less than the result. |
| 3 | RM - Round Towards Minus Infinity Rounds the result to the value closest to but not greater than the result. |

3.5.6 Operation of the FS/FO/FN Bits

The FS, FO, and FN bits in the CP1 *FCSR* register control handling of denormalized operands and *tiny* results (i.e. nonzero result between $\pm 2^{E_{min}}$), whereby the FPU can handle these cases right away instead of relying on the much slower software handler. The trade-off is a loss of IEEE compliance and accuracy (except for use of the FO bit), because a minimal normalized or zero result is provided by the FPU instead of the more accurate denormalized result that a software handler would give. The benefit is a significantly improved performance and precision.

Use of the FS, FO, and FN bits affects handling of denormalized floating-point numbers and tiny results for the instructions listed below:

FS and FN bit: ADD, CEIL, CVT, DIV, FLOOR, MADD, MSUB, MUL, NMADD, NMSUB, RECIP, ROUND, RSQRT, SQRT, TRUNC, SUB, ABS, C.cond, and NEG¹

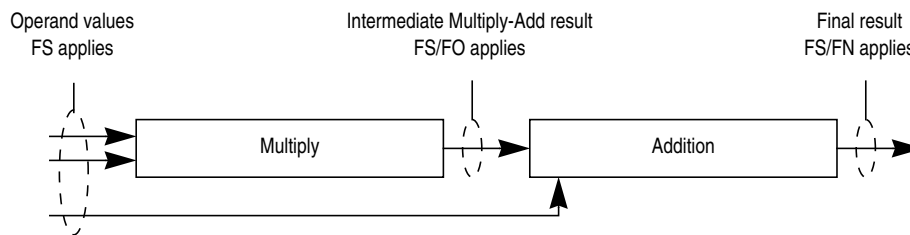
FO bit: MADD, MSUB, NMADD, and NMSUB

1. For ABS, C.cond, and NEG, denormal input operands or tiny results do not result in Unimplemented exceptions when FS = 0. Flushing to zero nonetheless is implemented when FS = 1 such that these operations return the same result as an equivalent sequence of arithmetic FPU operations.

Instructions not listed above do not cause Unimplemented Operation exceptions on denormalized numbers in operands or results.

Figure 3.16 depicts how the FS, FO, and FN bits control handling of denormalized numbers. For instructions that are not multiply or add types (such as DIV), only the FS and FN bits apply.

Figure 3.16 FS/FO/FN Bits Influence on Multiply and Addition Results



3.5.6.1 Flush To Zero Bit

When the Flush To Zero (FS) bit is set, denormal input operands are flushed to zero. Tiny results are flushed to either zero or the applied format's smallest normalized number (MinNorm) depending on the rounding mode settings. Table 3.13 lists the flushing behavior for tiny results..

Table 3.13 Zero Flushing for Tiny Results

| Rounding Mode | Negative Tiny Result | Positive Tiny Result |
|---------------|----------------------|----------------------|
| RN (RM=0) | -0 | +0 |
| RZ(RM=1) | -0 | +0 |
| RP (RM=2) | -0 | +MinNorm |
| RM (RM=3) | -MinNorm | +0 |

The flushing of results is based on an intermediate result computed by rounding the mantissa using an unbounded exponent range; that is, tiny numbers are not *normalized* into the supported exponent range by shifting in leading zeros prior to rounding.

Handling of denormalized operand values and tiny results depends on the FS bit setting as shown in Table 3.14.

Table 3.14 Handling of Denormalized Operand Values and Tiny Results Based on FS Bit Setting

| FS Bit | Handling of Denormalized Operand Values |
|--------|--|
| 0 | An Unimplemented Operation exception is taken. |

Table 3.14 Handling of Denormalized Operand Values and Tiny Results Based on FS Bit Setting

| FS Bit | Handling of Denormalized Operand Values |
|--------|--|
| 1 | Instead of causing an Unimplemented Operation exception, operands are flushed to zero, and tiny results are forced to zero or MinNorm. |

3.5.6.2 Flush Override Bit

When the Flush Override (FO) bit is set, a tiny intermediate result of any multiply-add type instruction is not flushed according to the FS bit. The intermediate result is maintained in an internal normalized format to improve accuracy. FO only applies to the intermediate result of a multiply-add type instruction.

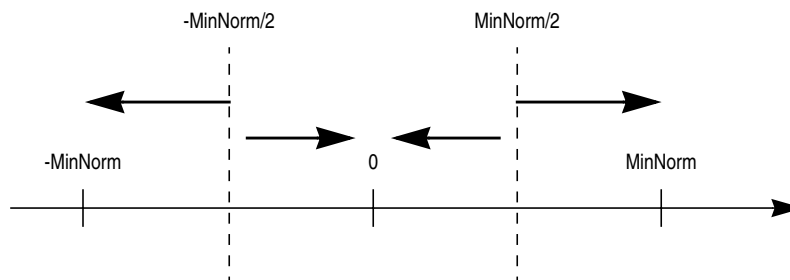
Handling of tiny intermediate results depends on the FO and FS bits as shown in [Table 3.15](#).

Table 3.15 Handling of Tiny Intermediate Result Based on the FO and FS Bit Settings

| FO Bit | FS Bit | Handling of Tiny Result Values |
|--------|------------|--|
| 0 | 0 | An Unimplemented Operation exception is taken. |
| 0 | 1 | The intermediate result is forced to the value that would have been delivered for an untrapped underflow (see Table 3.32) instead of causing an Unimplemented Operation exception. |
| 1 | Don't care | The intermediate result is kept in an internal format, which can be perceived as having the usual mantissa precision but with unlimited exponent precision and without forcing to a specific value or taking an exception. |

3.5.6.3 Flush to Nearest

When the Flush to Nearest (FN) bit is set and the rounding mode is Round to Nearest (RN), a tiny final result is flushed to zero or MinNorm. If a tiny number is strictly below MinNorm/2, the result is flushed to zero; otherwise, it is flushed to MinNorm (see [Figure 3.17](#)). The flushed result has the same sign as the result prior to flushing. Note that the FN bit takes precedence over the FS bit.

Figure 3.17 Flushing to Nearest when Rounding Mode is Round to Nearest

For all rounding modes other than Round to Nearest (RN), setting the FN bit causes final results to be flushed to zero or MinNorm as if the FS bit was set.

Handling of tiny final results depends on the FN and FS bits as shown in [Table 3.16](#).

Table 3.16 Handling of Tiny Final Result Based on FN and FS Bit Settings

| FN Bit | FS Bit | Handling of Tiny Result Values |
|--------|--------|--|
| 0 | 0 | An Unimplemented Operation exception is taken. |

Table 3.16 Handling of Tiny Final Result Based on FN and FS Bit Settings (Continued)

| FN Bit | FS Bit | Handling of Tiny Result Values |
|--------|------------|--|
| 0 | 1 | Final result is forced to the value that would have been delivered for an untrapped under-flow (see Table 3.32) rather than causing an Unimplemented Operation exception. |
| 1 | Don't care | Final result is rounded to either zero or $2^{E_{\min}}$ (MinNorm), whichever is closest when in Round to Nearest (RN) rounding mode. For other rounding modes, a final result is given as if FS was set to 1. |

3.5.6.4 Recommended FS/FO/FN Settings

Table 3.17 summarizes the recommended FS/FO/FN settings.

Table 3.17 Recommended FS/FO/FN Settings

| FS Bit | FO Bit | FN Bit | Remarks |
|--------|--------|--------|--|
| 0 | 0 | 0 | IEEE-compliant mode. Low performance on denormal operands and tiny results. |
| 1 | 0 | 0 | Regular embedded applications. High performance on denormal operands and tiny results. |
| 1 | 1 | 1 | Highest accuracy and performance configuration. ¹ |

1. Note that in this mode, MADD might return a different result other than the equivalent MUL and ADD operation sequence.

3.5.7 FCSR Cause Bit Update Flow

3.5.7.1 Exceptions Triggered by CTC1

Regardless of the targeted control register, the CTC1 instruction causes the Enables and Cause fields of the *FCSR* to be inspected in order to determine if an exception is to be thrown.

3.5.7.2 Generic Flow

Computations are performed in two steps:

1. Compute rounded mantissa with unbound exponent range.
2. Flush to default result if the result from Step #1 above is overflow or tiny (no flushing happens on denorms for instructions supporting denorm results, such as MOV).

The Cause field is updated after each of these two steps. Any enabled exceptions detected in these two steps cause a trap, and no further updates to the Cause field are done by subsequent steps.

Step #1 can set cause bits I, U, O, Z, V, and E. E has priority over V; V has priority over Z; and Z has priority over U and O. Thus when E, V, or Z is set in Step #1, no other cause bits can be set. However, note that I and V both can be set if a denormal operand was flushed (FS = 1). I, U, and O can be set alone or in pairs (IU or IO). U and O never can be set simultaneously in Step #1. U and O are set if the computed unbounded exponent is outside the exponent range supported by the normalized IEEE format.

Step #2 can set I if a default result is generated.

3.5.7.3 Multiply-Add Flow

For multiply-add type instructions, the computation is extended with two more steps:

1. Compute rounded mantissa with unbound exponent range for the multiply.
2. Flush to default result if the result from Step #1 is overflow or tiny (no flushing happens on tiny results if FO = 1).
3. Compute rounded mantissa with unbounded exponent range for the add.
4. Flush to default result if the result from Step #3 is overflow or tiny.

The Cause field is updated after each of these four steps. Any enabled exceptions detected in these four steps cause a trap, and no further updates to the Cause field are done by subsequent steps.

Step #1 and Step #3 can set a cause bit as described for Step #1 in [Section 3.5.7.2 “Generic Flow”](#).

Step #2 and Step #4 can set I if a default result is generated.

Although U and O can never both be set in Step #1 or Step #3, both U and O might be set after the multiply-add has executed in Step #3 because U might be set in Step #1 and O might be set in Step #3.

3.5.7.4 Cause Update Flow for Input Operands

Denormal input operands to Step #1 or Step #3 always set Cause bit I when FS = 1. For example, SNaN+DeNorm set I (and V) provided that Step #3 was reached (in case of a multiply-add type instruction).

Conditions directly related to the input operand (for example, I/E set due to DeNorm, V set due to SNaN and QNaN propagation) are detected in the step where the operand is logically used. For example, for multiply-add type instructions, exceptional conditions caused by the input operand fr are detected in Step #3.

3.5.7.5 Cause Update Flow for Unimplemented Operations

Note that Cause bit E is special; it clears any Cause updates done in previous steps. For example, if Step #3 caused E to be set, any I, U, or O Cause update done in Step #1 or Step #2 is cleared. Only E is set in the Cause field when an Unimplemented Operation trap is taken.

3.6 Instruction Overview

The functional groups into which the FPU instructions are divided are described in the following subsections:

- [Section 3.6.1 “Data Transfer Instructions”](#)
- [Section 3.6.2 “Arithmetic Instructions”](#)
- [Section 3.6.3 “Conversion Instructions”](#)
- [Section 3.6.4 “Formatted Operand-Value Move Instructions”](#)
- [Section 3.6.5 “Conditional Branch Instructions”](#)

- [Section 3.6.6 “Miscellaneous Instructions”](#)

The instructions are described in detail in [Chapter 12, “24K® Processor Core Instructions”](#) on page 303, including descriptions of supported formats (fmt).

3.6.1 Data Transfer Instructions

The FPU has two separate register sets: coprocessor general registers (FPRs) and coprocessor control registers (FCRs). The FPU has a load/store architecture; all computations are done on data held in coprocessor general registers. The control registers are used to control FPU operation. Data is transferred between registers and the rest of the system with dedicated load, store, and move instructions. The transferred data is treated as unformatted binary data; no format conversions are performed, and therefore no IEEE floating-point exceptions can occur.

[Table 3.18](#) lists the supported transfer operations.

Table 3.18 FPU Data Transfer Instructions

| Transfer Direction | | | Data Transferred |
|----------------------|---|----------------------|----------------------------|
| FPU general register | ↔ | Memory | Word/doubleword load/store |
| FPU general register | ↔ | CPU general register | Word move |
| FPU control register | ↔ | CPU general register | Word move |

3.6.1.1 Data Alignment in Loads, Stores, and Moves

All coprocessor loads and stores operate on naturally aligned data items. An attempt to load or store to an address that is not naturally aligned for the data item causes an Address Error exception. Regardless of byte ordering (the endianness), the address of a word or doubleword is the smallest byte address in the object. For a big-endian machine, this is the most-significant byte; for a little-endian machine, this is the least-significant byte.

3.6.1.2 Addressing Used in Data Transfer Instructions

The FPU has loads and stores using the same register+offset addressing as that used by the CPU. Moreover, for the FPU only, there are load and store instructions using *register+register* addressing.

Tables [3.19](#) through [3.20](#) list the FPU data transfer instructions.

Table 3.19 FPU Loads and Stores Using Register+Offset Address Mode

| Mnemonic | Instruction |
|----------|------------------------------------|
| LDC1 | Load Doubleword to Floating Point |
| LWC1 | Load Word to Floating Point |
| SDC1 | Store Doubleword to Floating Point |
| SWC1 | Store Word to Floating Point |

Table 3.20 FPU Move To and From Instructions

| Mnemonic | Instruction |
|----------|---------------------------------------|
| CFC1 | Move Control Word From Floating Point |
| CTC1 | Move Control Word To Floating Point |
| MFC1 | Move Word From Floating Point |
| MTC1 | Move Word To Floating Point |

3.6.2 Arithmetic Instructions

Arithmetic instructions operate on formatted data values. The results of most floating-point arithmetic operations meet IEEE Standard 754 for accuracy—a result is identical to an infinite-precision result that has been rounded to the specified format using the current rounding mode. The rounded result differs from the exact result by less than one Unit in the Least-significant Place (ULP).

In general, the arithmetic instructions take an Unimplemented Operation exception for denormalized numbers, except for the ABS, C, and NEG instructions, which can handle denormalized numbers. The FS, FO, and FN bits in the CP1 *FCSR* register can override this behavior as described in [Section 3.5.6 “Operation of the FS/FO/FN Bits”](#).

[Table 3.21](#) lists the FPU IEEE compliant arithmetic operations.

Table 3.21 FPU IEEE Arithmetic Operations

| Mnemonic | Instruction |
|------------|-------------------------------|
| ABS.fmt | Floating-Point Absolute Value |
| ADD.fmt | Floating-Point Add |
| C.cond.fmt | Floating-Point Compare |
| DIV.fmt | Floating-Point Divide |
| MUL.fmt | Floating-Point Multiply |
| NEG.fmt | Floating-Point Negate |
| SQRT.fmt | Floating-Point Square Root |
| SUB.fmt | Floating-Point Subtract |

The two low latency operations, Reciprocal Approximation (RECIP) and Reciprocal Square Root Approximation (RSQRT), might be less accurate than the IEEE specification:

- The result of RECIP differs from the exact reciprocal by no more than one ULP.
- The result of RSQRT differs from the exact reciprocal square root by no more than two ULPs.

[Table 3.22](#) lists the FPU-approximate arithmetic operations.

Table 3.22 FPU-Approximate Arithmetic Operations

| Mnemonic | Instruction |
|-----------|---|
| RECIP.fmt | Floating-Point Reciprocal Approximation |

Table 3.22 FPU-Approximate Arithmetic Operations (Continued)

| Mnemonic | Instruction |
|-----------|---|
| RSQRT.fmt | Floating-Point Reciprocal Square Root Approximation |

Four compound-operation instructions perform variations of multiply-accumulate operations; that is, multiply two operands, accumulate the result to a third operand, and produce a result. These instructions are listed in [Table 3.23](#). The product is rounded according to the current rounding mode prior to the accumulation. This model meets the IEEE accuracy specification; the result is numerically identical to an equivalent computation using multiply, add, subtract, or negate instructions.

Table 3.23 FPU Multiply-Accumulate Arithmetic Operations

| Mnemonic | Instruction |
|-----------|---|
| MADD.fmt | Floating-Point Multiply Add |
| MSUB.fmt | Floating-Point Multiply Subtract |
| NMADD.fmt | Floating-Point Negative Multiply Add |
| NMSUB.fmt | Floating-Point Negative Multiply Subtract |

3.6.3 Conversion Instructions

These instructions perform conversions between floating-point and fixed-point data types. Each instruction converts values from a number of operand formats to a particular result format. Some conversion instructions use the rounding mode specified in the Floating Control/Status register (*FCSR*), while others specify the rounding mode directly.

In general, the conversion instructions only take an Unimplemented Operation exception for denormalized numbers. The FS and FN bits in the CP1 *FCSR* register can override this behavior as described in [Section 3.5.6 “Operation of the FS/FO/FN Bits”](#).

[Table 3.24](#) and [Table 3.25](#) list the FPU conversion instructions according to their rounding mode.

Table 3.24 FPU Conversion Operations Using the FCSR Rounding Mode

| Mnemonic | Instruction |
|-----------|---|
| CVT.D.fmt | Floating-Point Convert to Double Floating Point |
| CVT.L.fmt | Floating-Point Convert to Long Fixed Point |
| CVT.S.fmt | Floating-Point Convert to Single Floating Point |
| CVT.W.fmt | Floating-Point Convert to Word Fixed Point |

Table 3.25 FPU Conversion Operations Using a Directed Rounding Mode

| Mnemonic | Instruction |
|-------------|--|
| CEIL.L.fmt | Floating-Point Ceiling to Long Fixed Point |
| CEIL.W.fmt | Floating-Point Ceiling to Word Fixed Point |
| FLOOR.L.fmt | Floating-Point Floor to Long Fixed Point |
| FLOOR.W.fmt | Floating-Point Floor to Word Fixed Point |
| ROUND.L.fmt | Floating-Point Round to Long Fixed Point |

Table 3.25 FPU Conversion Operations Using a Directed Rounding Mode (Continued)

| Mnemonic | Instruction |
|-------------|---|
| ROUND.W.fmt | Floating-Point Round to Word Fixed Point |
| TRUNC.L.fmt | Floating-Point Truncate to Long Fixed Point |
| TRUNC.W.fmt | Floating-Point Truncate to Word Fixed Point |

3.6.4 Formatted Operand-Value Move Instructions

These instructions move formatted operand values among FPU general registers. A particular operand type must be moved by the instruction that handles that type. There are three kinds of move instructions:

- Unconditional move
- Conditional move that tests an FPU true/false condition code
- Conditional move that tests a CPU general-purpose register against zero

Conditional move instructions operate in a way that might be unexpected. They always force the value in the destination register to become a value of the format specified in the instruction. If the destination register does not contain an operand of the specified format before the conditional move is executed, the contents become undefined. (For more information, see the individual descriptions of the conditional move instructions in the *MIPS32 Architecture Reference Manual, Volume II* [2].)

Table 3.26 through Table 3.28 list the formatted operand-value move instructions.

Table 3.26 FPU Formatted Operand Move Instruction

| Mnemonic | Instruction |
|----------|---------------------|
| MOV.fmt | Floating-Point Move |

Table 3.27 FPU Conditional Move on True/False Instructions

| Mnemonic | Instruction |
|----------|---|
| MOVE.fmt | Floating-Point Move Conditional on FP False |
| MOVT.fmt | Floating-Point Move Conditional on FP True |

Table 3.28 FPU Conditional Move on Zero/Non-Zero Instructions

| Mnemonic | Instruction |
|----------|--|
| MOVN.fmt | Floating-Point Move Conditional on Nonzero |
| MOVZ.fmt | Floating-Point Move Conditional on Zero |

3.6.5 Conditional Branch Instructions

The FPU has PC-relative conditional branch instructions that test condition codes set by FPU compare instructions (C.cond.fmt).

All branches have an architectural delay of one instruction. When a branch is taken, the instruction immediately following the branch instruction is said to be in the branch delay slot; it is executed before the branch to the target instruction takes place. Conditional branches come in two versions, depending upon how they handle an instruction in the delay slot when the branch is not taken and execution falls through:

- Branch instructions execute the instruction in the delay slot.
- Branch likely instructions do not execute the instruction in the delay slot if the branch is not taken (they are said to nullify the instruction in the delay slot).

Although the Branch Likely instructions are included, software is strongly encouraged to avoid the use of the Branch Likely instructions, as they will be removed from a future revision of the MIPS Architecture.

The MIPS64 architecture defines eight condition codes for use in compare and branch instructions. For backward compatibility with previous revisions of the ISA, condition code bit 0 and condition code bits 1 through 7 are in discontinuous fields in the *FCSR*.

Table 3.29 lists the conditional branch (branch and branch likely) FPU instructions; Table 3.30 lists the deprecated conditional branch likely instructions.

Table 3.29 FPU Conditional Branch Instructions

| Mnemonic | Instruction |
|----------|--------------------|
| BC1F | Branch on FP False |
| BC1T | Branch on FP True |

Table 3.30 Deprecated FPU Conditional Branch Likely Instructions

| Mnemonic | Instruction |
|----------|---------------------------|
| BC1FL | Branch on FP False Likely |
| BC1TL | Branch on FP True Likely |

3.6.6 Miscellaneous Instructions

The MIPS32 architecture defines various miscellaneous instructions that conditionally move one CPU general register to another, based on an FPU condition code.

Table 3.31 lists these conditional move instructions.

Table 3.31 CPU Conditional Move on FPU True/False Instructions

| Mnemonic | Instruction |
|----------|------------------------------|
| MOVN | Move Conditional on FP False |
| MOVZ | Move Conditional on FP True |

3.7 Exceptions

FPU exceptions are implemented in the MIPS FPU architecture with the Cause, Enables, and Flags fields of the *FCSR*. The flag bits implement IEEE exception status flags, and the cause and enable bits control exception trapping. Each field has a bit for each of the five IEEE exception conditions. The Cause field has an additional exception bit, Unimplemented Operation, used to trap for software emulation assistance. If an exception type is enabled through the Enables field of the *FCSR*, then the FPU is operating in precise exception mode for this type of exception.

3.7.1 Precise Exception Mode

In precise exception mode, a trap occurs before the instruction that causes the trap or any following instruction can complete and write its results. If desired, the software trap handler can resume execution of the interrupted instruction stream after handling the exception.

The Cause field reports per-bit instruction exception conditions. The cause bits are written during each floating-point arithmetic operation to show any exception conditions that arise during the operation. A cause bit is set to 1 if its corresponding exception condition arises; otherwise, it is cleared to 0.

A floating-point trap is generated any time both a cause bit and its corresponding enable bit are set. This case occurs either during the execution of a floating-point operation or when moving a value into the *FCSR*. There is no enable bit for Unimplemented Operations; this exception always generates a trap.

In a trap handler, exception conditions that arise during any trapped floating-point operations are reported in the Cause field. Before returning from a floating-point interrupt or exception, or before setting cause bits with a move to the *FCSR*, software first must clear the enabled cause bits by executing a move to the *FCSR* to prevent the trap from being erroneously retaken.

If a floating-point operation sets only non-enabled cause bits, no trap occurs and the default result defined by IEEE Standard 754 is stored (see [Table 3.32](#)). When a floating-point operation does not trap, the program can monitor the exception conditions by reading the Cause field.

The Flags field is a cumulative report of IEEE exception conditions that arise as instructions complete; instructions that trap do not update the flag bits. The flag bits are set to 1 if the corresponding IEEE exception is raised, otherwise the bits are unchanged. There is no flag bit for the MIPS Unimplemented Operation exception. The flag bits are never cleared as a side effect of floating-point operations, but they can be set or cleared by moving a new value into the *FCSR*.

3.7.2 Exception Conditions

The subsections below describe the following five exception conditions defined by IEEE Standard 754:

- [Section 3.7.2.1 “Invalid Operation Exception”](#)
- [Section 3.7.2.2 “Division By Zero Exception”](#)
- [Section 3.7.2.3 “Underflow Exception”](#)
- [Section 3.7.2.4 “Overflow Exception”](#)
- [Section 3.7.2.5 “Inexact Exception”](#)

Section 3.7.2.6 “Unimplemented Operation Exception” also describes a MIPS-specific exception condition, Unimplemented Operation Exception, that is used to signal a need for software emulation of an instruction. Normally an IEEE arithmetic operation can cause only one exception condition; the only case in which two exceptions can occur at the same time are Inexact With Overflow and Inexact With Underflow.

At the program’s direction, an IEEE exception condition can either cause a trap or not cause a trap. IEEE Standard 754 specifies the result to be delivered in case no trap is taken. The FPU supplies these results whenever the exception condition does not result in a trap. The default action taken depends on the type of exception condition and, in the case of the Overflow and Underflow, the current rounding mode. Table 3.32 summarizes the default results.

Table 3.32 Result for Exceptions Not Trapped

| Bit | Description | Default Action |
|-----|-------------------|---|
| V | Invalid Operation | Supplies a quiet NaN. |
| Z | Divide by zero | Supplies a properly signed infinity. |
| U | Underflow | Depends on the rounding mode as shown below: 0 (RN) and 1 (RZ): Supplies a zero with the sign of the exact result. 2 (RP): For positive underflow values, supplies $2^{E_{\min}}$ (MinNorm). For negative underflow values, supplies a positive zero. 3 (RM): For positive underflow values, supplies a negative zero. For negative underflow values, supplies a negative $2^{E_{\min}}$ (MinNorm). Note that this behavior is only valid if the $FCSR_{FN}$ bit is cleared. |
| I | Inexact | Supplies a rounded result. If caused by an overflow without the overflow trap enabled, supplies the overflowed result. If caused by an underflow without the underflow trap enabled, supplies the underflowed result. |
| O | Overflow | Depends on the rounding mode, as shown below: 0 (RN): Supplies an infinity with the sign of the exact result. 1 (RZ): Supplies the format’s largest finite number with the sign of the exact result. 2 (RP): For positive overflow values, supplies positive infinity. For negative overflow values, supplies the format’s most negative finite number. 3 (RM): For positive overflow values, supplies the format’s largest finite number. For negative overflow values, supplies minus infinity. |

3.7.2.1 Invalid Operation Exception

An Invalid Operation exception is signaled when one or both of the operands are invalid for the operation to be performed. When the exception condition occurs without a precise trap, the result is a quiet NaN.

The following operations are invalid:

- One or both operands are a signaling NaN (except for the non-arithmetic MOV.fmt, MOVT.fmt, MOVF.fmt, MOVN.fmt, and MOVZ.fmt instructions).
- Addition or subtraction: magnitude subtraction of infinities, such as $(+\infty) + (-\infty)$ or $(-\infty) - (-\infty)$.
- Multiplication: $0 \times \infty$, with any signs.
- Division: $0/0$ or ∞/∞ , with any signs.
- Square root: An operand of less than 0 (-0 is a valid operand value).

- Conversion of a floating-point number to a fixed-point format when either an overflow or an operand value of infinity or NaN precludes a faithful representation in that format.
- Some comparison operations in which one or both of the operands is a QNaN value.

3.7.2.2 Division By Zero Exception

The divide operation signals a Division By Zero exception if the divisor is zero and the dividend is a finite nonzero number. When no precise trap occurs, the result is a correctly signed infinity. Divisions (0/0 and $\infty/0$) do not cause the Division By Zero exception. The result of (0/0) is an Invalid Operation exception. The result of ($\infty/0$) is a correctly signed infinity.

3.7.2.3 Underflow Exception

Two related events contribute to underflow:

- **Tininess:** The creation of a tiny, nonzero result between $\pm 2^{E_{min}}$ which, because it is tiny, might cause some other exception later such as overflow on division. IEEE Standard 754 allows choices in detecting tininess events. The MIPS architecture specifies that tininess be detected after rounding, when a nonzero result computed as though the exponent range were unbounded would lie strictly between $\pm 2^{E_{min}}$.
- **Loss of accuracy:** The extraordinary loss of accuracy occurs during the approximation of such tiny numbers by denormalized numbers. IEEE Standard 754 allows choices in detecting loss of accuracy events. The MIPS architecture specifies that loss of accuracy be detected as inexact result, when the delivered result differs from what would have been computed if both the exponent range and precision were unbounded.

The way that an underflow is signaled depends on whether or not underflow traps are enabled:

- When an underflow trap is not enabled, underflow is signaled only when both tininess and loss of accuracy have been detected. The delivered result might be zero, denormalized, or $\pm 2^{E_{min}}$.
- When an underflow trap is enabled (through the *FCSR* Enables field), underflow is signaled when tininess is detected regardless of loss of accuracy.

3.7.2.4 Overflow Exception

An Overflow exception is signaled when the magnitude of a rounded floating-point result (if the exponent range is unbounded) is larger than the destination format's largest finite number.

When no precise trap occurs, the result is determined by the rounding mode and the sign of the intermediate result.

3.7.2.5 Inexact Exception

An Inexact exception is signaled when one of the following occurs:

- The rounded result of an operation is not exact.
- The rounded result of an operation overflows without an overflow trap.
- When a denormal operand is flushed to zero.

3.7.2.6 Unimplemented Operation Exception

The Unimplemented Operation exception is a MIPS-defined exception that provides software emulation support. This exception is not IEEE-compliant.

The MIPS architecture is designed so that a combination of hardware and software can implement the architecture. Operations not fully supported in hardware cause an Unimplemented Operation exception, allowing software to perform the operation.

There is no enable bit for this condition; it always causes a trap (but the condition is effectively masked for all operations when FS=1). After the appropriate emulation or other operation is done in a software exception handler, the original instruction stream can be continued.

An Unimplemented Operation exception is taken in the following situations:

- when denormalized operands or tiny results are encountered for instructions not supporting denormal numbers and where such are not handed by the FS/FO/FN bits.

3.8 Pipeline and Performance

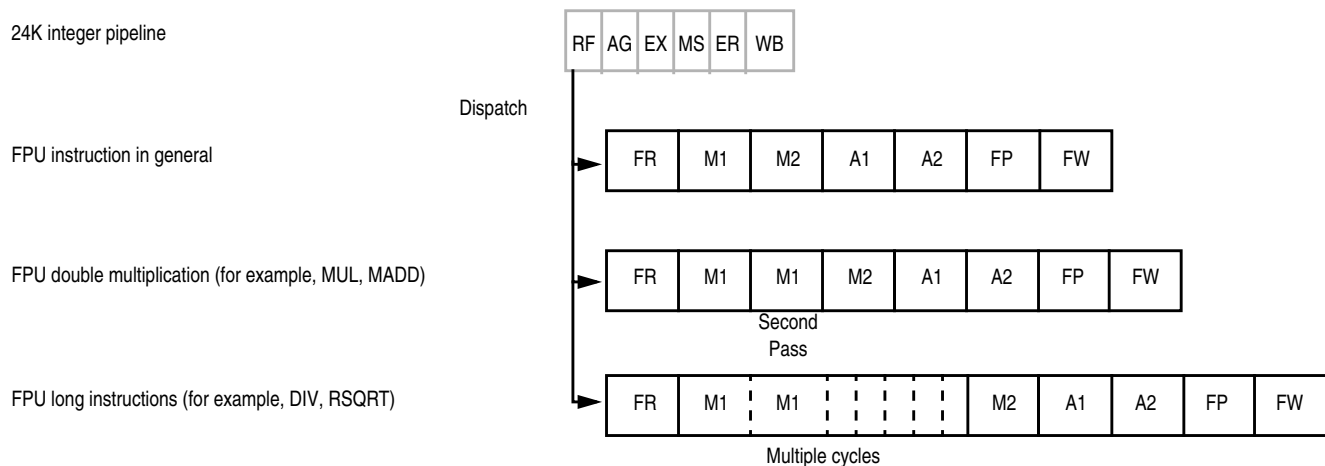
This section describes the structure and operation of the FPU pipeline.

3.8.1 Pipeline Overview

The FPU has a seven stage pipeline to which the integer pipeline dispatches instructions. The FPU pipeline runs in parallel with the 24K integer pipeline. The FPU can be built to run at either the same frequency as the integer core or at one-half the frequency of the integer core.

The FPU pipe is optimized for single-precision instructions, such that the basic multiply, ADD/SUB, and MADD/MSUB instructions can be performed with single-cycle throughput and low latency. Executing double-precision multiply and MADD/MSUB instructions requires a second pass through the M1 stage to generate all 64 bits of the product. Executing long latency instructions, such as DIV and RSQRT, extends the M1 stage. [Figure 3.18](#) shows the FPU pipeline.

Figure 3.18 FPU Pipeline



3.8.1.1 FR Stage - Decode, Register Read, and Unpack

The FR stage has the following functionality:

- The dispatched instruction is decoded for register accesses.
- Data is read from the register file.
- The operands are unpacked into an internal format.

3.8.1.2 M1 Stage - Multiply Tree

The M1 stage has the following functionality:

- A single-cycle multiply array is provided for single-precision data format multiplication, and two cycles are provided for double-precision data format multiplication.
- The long instructions, such as divide and square root, iterate for several cycles in this stage.
- Sum of exponents is calculated.

3.8.1.3 M2 Stage - Multiply Complete

The M2 stage has the following functionality:

- Multiplication is complete when the carry-save encoded product is compressed into binary.
- Rounding is performed.
- Exponent difference for addition path is calculated.

3.8.1.4 A1 Stage - Addition First Step

This stage performs the first step of the addition.

3.8.1.5 A2 Stage - Addition Second and Final Step

This stage performs the second and final step of the addition.

3.8.1.6 FP Stage - Result Pack

The FP stage has the following functionality:

- The result coming from the datapath is packed into IEEE 754 Standard format for the FPR register file.
- Overflow and underflow exceptional conditions are resolved.

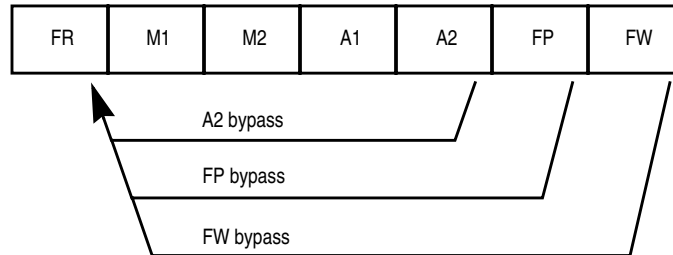
3.8.1.7 FW Stage - Register Write

The result is written to the FPR register file.

3.8.2 Bypassing

The FPU pipeline implements extensive bypassing, as shown in [Figure 3.19](#). Results do not need to be written into the register file and read back before they can be used, but can be forwarded directly to an instruction already in the pipe. Some bypassing is disabled when operating in 32-bit register file mode, the FP bit in the CP0 *Status* register is 0, due to the paired even-odd 32-bit registers that provide 64-bit registers.

Figure 3.19 Arithmetic Pipeline Bypass Paths



3.8.3 Repeat Rate and Latency

[Table 3.33](#) shows the repeat rate and latency for the FPU instructions. Note that cycles related to floating point operations are listed in terms of FPU clocks.

Table 3.33 24Kf Core FPU Latency and Repeat Rate

| Opcode ¹ | Latency (cycles) | Repeat Rate (cycles) |
|--|------------------|----------------------|
| ABS.[S,D], NEG.[S,D], ADD.[S,D], SUB.[S,D], MUL.S, MADD.S, MSUB.S, NMADD.S, NMSUB.S | 4 | 1 |
| MUL.D, MADD.D, MSUB.D, NMADD.D, NMSUB.D | 5 | 2 |
| RECIP.S | 13 | 10 |
| RECIP.D | 25 | 21 |
| RSQRT.S | 17 | 14 |
| RSQRT.D | 35 | 31 |
| DIV.S, SQRT.S | 17 | 14 |
| DIV.D, SQRT.D | 32 | 29 |
| C.cond.[S,D] to MOVF.fmt and MOVT.fmt instruction / MOVT, MOVN, BC1 instruction | 1 / 2 | 1 |
| CVT.D.S, CVT.[S,D].[W,L] | 4 | 1 |
| CVT.S.D | 6 | 1 |
| CVT.[W,L].[S,D], CEIL.[W,L].[S,D], FLOOR.[W,L].[S,D], ROUND.[W,L].[S,D], TRUNC.[W,L].[S,D] | 5 | 1 |
| MOV.[S,D], MOVF.[S,D], MOVN.[S,D], MOVT.[S,D], MOVZ.[S,D] | 4 | 1 |
| LWC1, LDC1, LDXC1, LUXC1, LWXC1 | 3 | 1 |
| MTC1, MFC1 | 2 | 1 |

1. Format: S = Single, D = Double, W = Word, L = Longword.

Memory Management of the 24K® Core

The 24K processor core includes a Memory Management Unit (MMU) that interfaces between the execution unit and the cache controller. The core contains either a Translation Lookaside Buffer (TLB) or a simpler Fixed Mapping (FM) style MMU, specified as a build-time option when the core is implemented.

This chapter contains the following sections:

- [Section 4.1 “Introduction”](#)
- [Section 4.2 “Modes of Operation”](#)
- [Section 4.3 “Translation Lookaside Buffer”](#)
- [Section 4.4 “Virtual-to-Physical Address Translation”](#)
- [Section 4.5 “Fixed Mapping MMU”](#)
- [Section 4.6 “System Control Coprocessor”](#)

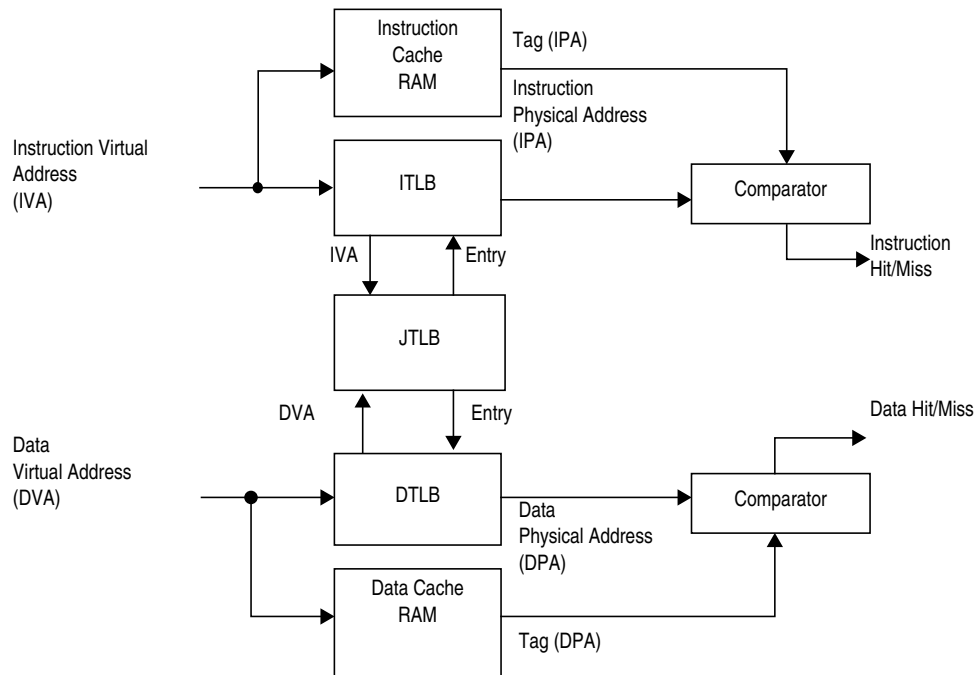
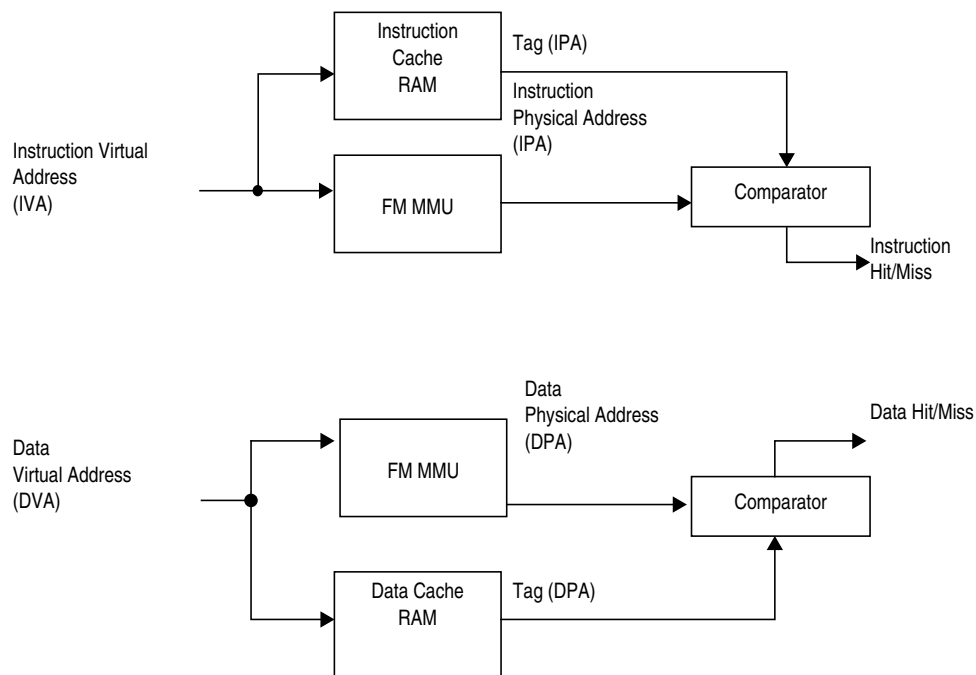
4.1 Introduction

The MMU in a 24K processor core will translate any virtual address to a physical address before a request is sent to the cache controllers for tag comparison or to the bus interface unit for an external memory reference. This translation is a very useful feature for operating systems when trying to manage physical memory to accommodate multiple tasks active in the same memory, possibly on the same virtual address but of course in different locations in physical memory. Other features handled by the MMU are protection of memory areas and defining the cache protocol.

By default, the MMU is TLB based. The TLB consists of three address translation buffers: a 16/32/64 dual-entry fully associative Joint TLB (JTLB), a 4-entry instruction micro TLB (ITLB), and an 8-entry data micro TLB (DTLB). When an address is translated, the appropriate micro TLB (ITLB or DTLB) is accessed first. If the translation is not found in the micro TLB, the JTLB is accessed. If there is a miss in the JTLB, an exception is taken.

Optionally, the MMU can be based on a simple algorithm to translate virtual addresses into physical addresses via a Fixed Mapping (FM) mechanism. These translations are different for various regions of the virtual address space (useg/kuseg, kseg0, kseg1, kseg2/3).

[Figure 4.1](#) shows how the memory management unit interacts with cache accesses with a TLB, while [Figure 4.2](#) shows the equivalent for the FM MMU.

Figure 4.1 Address Translation During a Cache Access with TLB MMU**Figure 4.2 Address Translation During a Cache Access with FM MMU**

4.2 Modes of Operation

A 24K processor core supports four modes of operation:

- User mode
- Supervisor mode (only w/ TLB)
- Kernel mode
- Debug mode

User mode is most often used for application programs. Supervisor mode has an intermediate privilege level with access to an additional region of memory and is only supported with the TLB-based MMU. Kernel mode is typically used for handling exceptions and privileged operating system functions, including CP0 management and I/O device accesses. Debug mode is used for software debugging and most likely occurs within a software development tool.

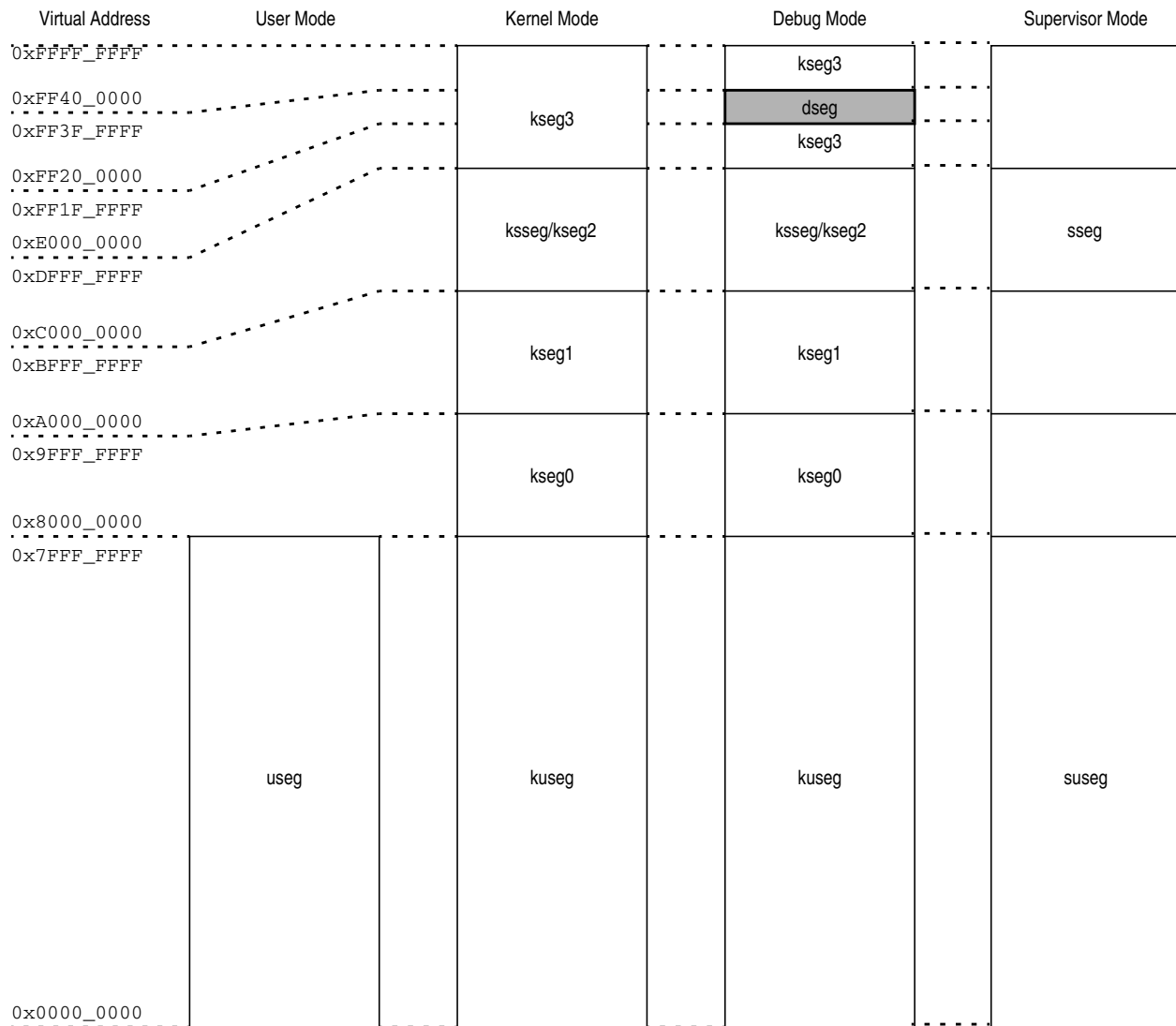
The address translation performed by the MMU depends on the mode in which the processor is operating.

4.2.1 Virtual Memory Segments

The Virtual memory segments are different depending on the mode of operation. [Figure 4.3](#) shows the segmentation for the 4 GByte (2^{32} bytes) virtual memory space addressed by a 32-bit virtual address, for the four modes of operation.

The core enters Kernel mode both at reset and when an exception is recognized. While in Kernel mode, software has access to the entire address space, as well as all CP0 registers. User mode accesses are limited to a subset of the virtual address space (0x0000_0000 to 0x7FFF_FFFF) and can be inhibited from accessing CP0 functions. In User mode, virtual addresses 0x8000_0000 to 0xFFFF_FFFF are invalid and cause an exception if accessed. Supervisor mode adds access to sseg (0xC000_0000 to 0xDFFF_FFFF). kseg0, kseg1, and kseg3 will still cause exceptions if they are accessed.

Debug mode is entered on a debug exception. While in Debug mode, the debug software has access to the same address space and CP0 registers as for Kernel mode. In addition, while in Debug mode the core has access to the debug segment dseg. This area overlays part of the kernel segment kseg3. dseg access in Debug mode can be turned on or off, allowing full access to the entire kseg3 in Debug mode, if so desired.

Figure 4.3 24K® Processor Core Virtual Memory Map

Each of the segments shown in [Figure 4.3](#) are either mapped or unmapped. The following two sub-sections explain the distinction. Then sections [Section 4.2.2 “User Mode”](#), [Section 4.2.4 “Kernel Mode”](#), and [Section 4.2.5 “Debug Mode”](#) specify which segments are actually mapped and unmapped.

4.2.1.1 Unmapped Segments

An unmapped segment does not use the TLB or the FM to translate from virtual-to-physical addresses. Especially after reset, it is important to have unmapped memory segments, because the TLB is not yet programmed to perform the translation.

Unmapped segments have a fixed simple translation from virtual to physical address. This is much like the translations the FM provides for the core, but we will still make the distinction.

Except for kseg0, unmapped segments are always uncached. The cacheability of kseg0 is set in the *K0* field of the CP0 register *Config* (see [Section 6.2.21 “Config Register \(CP0 Register 16, Select 0\)”](#)).

4.2.1.2 Mapped Segments

A mapped segment does use the TLB or the FM to translate from virtual-to-physical addresses.

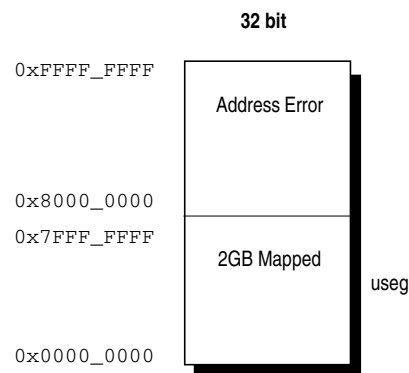
For the core with TLB, the translation of mapped segments is handled on a per-page basis. Included in this translation is information defining whether the page is cacheable or not, and the protection attributes that apply to the page.

For the core with the FM MMU, the mapped segments have a fixed translation from virtual to physical address. The cacheability of the segment is defined in the CP0 register *Config*, fields *K23* and *KU* (see [Section 6.2.21 “Config Register \(CP0 Register 16, Select 0\)”](#)). Write protection of segments is not possible during FM translation.

4.2.2 User Mode

In user mode, a single 2 GByte (2^{31} bytes) uniform virtual address space called the user segment (useg) is available. [Figure 4.4](#) shows the location of user mode virtual address space.

Figure 4.4 User Mode Virtual Address Space



The user segment starts at address 0x0000_0000 and ends at address 0x7FFF_FFFF. Accesses to all other addresses cause an address error exception.

The processor operates in User mode when the *Status* register contains the following bit values:

- *KSU* = 2#10
- *EXL* = 0
- *ERL* = 0

In addition to the above values, the *DM* bit in the *Debug* register must be 0.

Table 4.1 lists the characteristics of the User mode segment.

Table 4.1 User Mode Segments

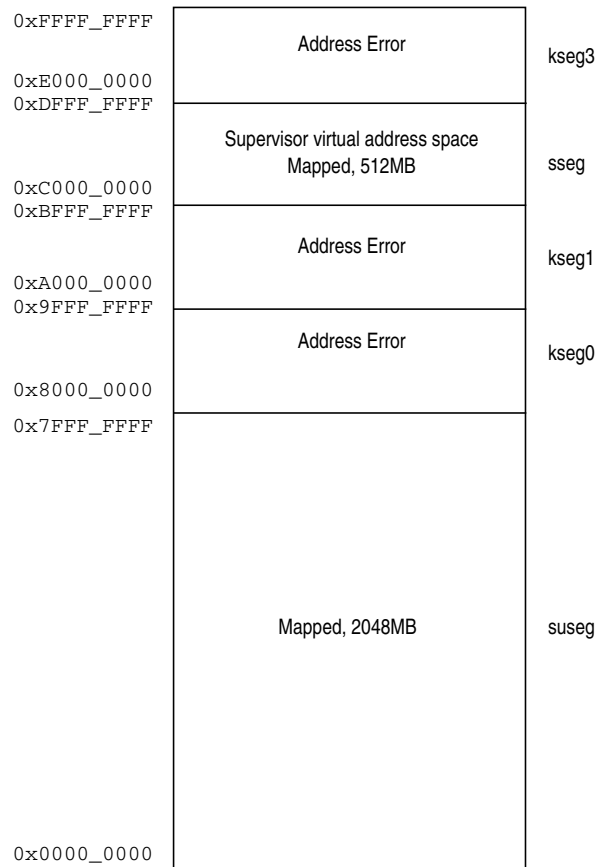
| Address Bit Value | Status Register | | | Segment Name | Address Range | Segment Size |
|---------------------|-----------------|-----|------|--------------|--------------------------------|------------------------------------|
| | Bit Value | | | | | |
| | EXL | ERL | KSU | | | |
| 32-bit A(31) = 0 | 0 | 0 | 2#10 | useg | 0x0000_0000 --> 0x7FFF_FFFF | 2 GByte (2 ³¹ bytes) |

All valid user mode virtual addresses have their most significant bit cleared to 0, indicating that user mode can only access the lower half of the virtual memory map. Any attempt to reference an address with the most significant bit set while in user mode causes an address error exception.

The system maps all references to useg through the TLB or FM. For cores with a TLB, the virtual address is extended with the contents of the 8-bit *ASID* field to form a unique virtual address before translation. Also bit settings within the TLB entry for the page determine the cacheability of a reference. For FM MMU cores, the cacheability is set via the *KU* field of the CP0 *Config* register.

4.2.3 Supervisor Mode

In supervisor mode, two virtual address spaces are available. A 2 GByte (2³¹ bytes) uniform virtual address space called the user segment (useg) as well as the 512MB (ksseg) are available. Figure 4.5 shows the location of supervisor mode virtual address space.

Figure 4.5 Supervisor Mode Virtual Address Space

The user segment starts at address 0x0000_0000 and ends at address 0x7FFF_FFFF. The supervisor segment begins at 0xC000_0000 and ends at 0xDFFF_FFFF. Accesses to all other addresses cause an address error exception.

The processor operates in Supervisor mode when the *Status* register contains the following bit values:

- $KSU = 2\#01$
- $EXL = 0$
- $ERL = 0$

In addition to the above values, the *DM* bit in the *Debug* register must be 0.

Table 4.1 lists the characteristics of the Supervisor mode segments.

Table 4.2 Supervisor Mode Segments

| Address Bit Value | Status Register | | | Segment Name | Address Range | Segment Size |
|---------------------------------------|-----------------|-----|------|--------------|--------------------------------|------------------------------------|
| | Bit Value | | | | | |
| | EXL | ERL | KSU | | | |
| 32-bit A(31) = 0 | 0 | 0 | 2#01 | suseg | 0x0000_0000 --> 0x7FFF_FFFF | 2 GByte (2 ³¹ bytes) |
| 32-bit A(31:29) = 110 ₂ | 0 | 0 | 2#01 | sseg | 0xC000_0000 -> 0xDFFF_FFFF | 512MB (2 ²⁹ bytes) |

The system maps all references to useg and ksseg through the TLB or FM. For cores with a TLB, the virtual address is extended with the contents of the 8-bit *ASID* field to form a unique virtual address before translation. Also bit settings within the TLB entry for the page determine the cacheability of a reference. For FM MMU cores, the cacheability of useg and ksseg is set via the *KU* and *K23* fields of the CP0 *Config* register respectively.

4.2.4 Kernel Mode

The processor operates in Kernel mode when the *DM* bit in the *Debug* register is 0 and the *Status* register contains one or more of the following values:

- *KSU* = 2#00
- *ERL* = 1
- *EXL* = 1

When a non-debug exception is detected, *EXL* or *ERL* will be set and the processor will enter Kernel mode. At the end of the exception handler routine, an Exception Return (ERET) instruction is generally executed. The ERET instruction jumps to the Exception PC, clears *ERL*, and clears *EXL* if *ERL*=0. This may return the processor to User mode.

Kernel mode virtual address space is divided into regions differentiated by the high-order bits of the virtual address, as shown in Figure 4.6. Also, Table 4.3 lists the characteristics of the Kernel mode segments.

Figure 4.6 Kernel Mode Virtual Address Space

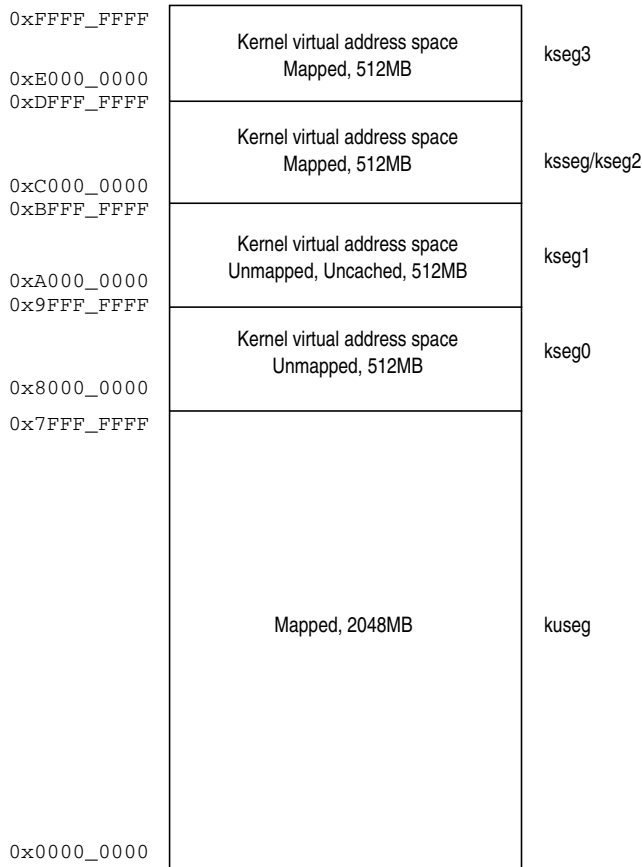


Table 4.3 Kernel Mode Segments

| Address Bit Values | Status Register Is One of These Values | | | Segment Name | Address Range | Segment Size |
|-----------------------------|--|-----|-----|--------------|---------------------------------------|------------------------------------|
| | KSU | EXL | ERL | | | |
| A(31) = 0 | (KSU = 00 ₂ or EXL = 1 or ERL = 1) and DM = 0 | | | kuseg | 0x0000_0000 through 0x7FFF_FFFF | 2 GBytes (2 ³¹ bytes) |
| A(31:29) = 100 ₂ | | | | kseg0 | 0x8000_0000 through 0x9FFF_FFFF | 512 MBytes (2 ²⁹ bytes) |
| A(31:29) = 101 ₂ | | | | kseg1 | 0xA000_0000 through 0xBFFF_FFFF | 512 MBytes (2 ²⁹ bytes) |
| A(31:29) = 110 ₂ | | | | ksseg/kseg2 | 0xC000_0000 through 0xDFFF_FFFF | 512 MBytes (2 ²⁹ bytes) |
| A(31:29) = 111 ₂ | | | | kseg3 | 0xE000_0000 through 0xFFFF_FFFF | 512 MBytes (2 ²⁹ bytes) |

4.2.4.1 Kernel Mode, User Space (kuseg)

In Kernel mode, when the most-significant bit of the virtual address (A31) is cleared, the 32-bit kuseg virtual address space is selected and covers the full 2³¹ bytes (2 GBytes) of the current user address space mapped to addresses 0x0000_0000 - 0x7FFF_FFFF. For cores with TLBs, the virtual address is extended with the contents of the 8-bit ASID field to form a unique virtual address.

When *ERL* = 1 in the *Status* register, the user address region becomes a 2³¹-byte unmapped and uncached address space. While in this setting, the kuseg virtual address maps directly to the same physical address, and does not include the *ASID* field.

4.2.4.2 Kernel Mode, Kernel Space 0 (kseg0)

In Kernel mode, when the most-significant three bits of the virtual address are 100₂, 32-bit kseg0 virtual address space is selected; it is the 2²⁹-byte (512-MByte) kernel virtual space located at addresses 0x8000_0000 - 0x9FFF_FFFF. References to kseg0 are unmapped; the physical address selected is defined by subtracting 0x8000_0000 from the virtual address. The *K0* field of the *Config* register controls cacheability.

4.2.4.3 Kernel Mode, Kernel Space 1 (kseg1)

In Kernel mode, when the most-significant three bits of the 32-bit virtual address are 101₂, 32-bit kseg1 virtual address space is selected. kseg1 is the 2²⁹-byte (512-MByte) kernel virtual space located at addresses 0xA000_0000 - 0xBFFF_FFFF. References to kseg1 are unmapped; the physical address selected is defined by subtracting 0xA000_0000 from the virtual address. Caches are disabled for accesses to these addresses, and physical memory (or memory-mapped I/O device registers) are accessed directly.

4.2.4.4 Kernel Mode, Kernel/Supervisor Space 2 (ksseg/kseg2)

In Kernel mode, when $KSU = 00_2$, $ERL = 1$, or $EXL = 1$ in the *Status* register, and $DM = 0$ in the *Debug* register, and the most-significant three bits of the 32-bit virtual address are 110_2 , 32-bit kseg2 virtual address space is selected.

With the FM MMU, this 2^{29} -byte (512-MByte) kernel virtual space is located at physical addresses $0xC000_0000 - 0xDFFF_FFFF$. Otherwise, this space is mapped through the TLB.

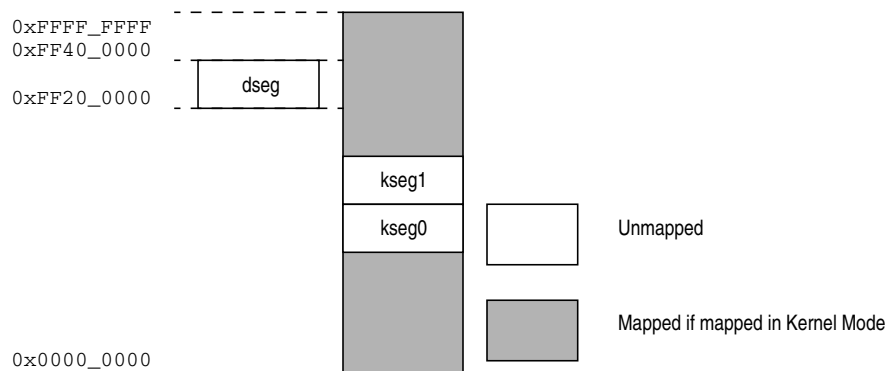
4.2.4.5 Kernel Mode, Kernel Space 3 (kseg3)

In Kernel mode, when the most-significant three bits of the 32-bit virtual address are 111_2 , the kseg3 virtual address space is selected. With the FM MMU, this 2^{29} -byte (512-MByte) kernel virtual space is located at physical addresses $0xE000_0000 - 0xFFFF_FFFF$. Otherwise, this space is mapped through the TLB.

4.2.5 Debug Mode

Debug mode address space is identical to Kernel mode address space with respect to mapped and unmapped areas, except for kseg3. In kseg3, a debug segment, dseg, co-exists in the virtual address range $0xFF20_0000$ to $0xFF3F_FFFF$. The layout is shown in Figure 4.7.

Figure 4.7 Debug Mode Virtual Address Space



The *dseg* is subdivided into the *dmseg* segment at $0xFF20_0000$ to $0xFF2F_FFFF$, which is used when the probe services the memory segment, and the *drseg* segment at $0xFF30_0000$ to $0xFF3F_FFFF$ which is used when memory-mapped debug registers are accessed. The subdivision and attributes for the segments are shown in Table 4.4.

Accesses to memory that would normally cause an exception if tried from kernel mode cause the core to re-enter debug mode via a debug mode exception. This includes accesses usually causing a TLB exception, with the result that such accesses are not handled by the usual memory management routines.

The unmapped kseg0 and kseg1 segments from kernel mode address space are available from debug mode, which allows the debug handler to be executed from uncached and unmapped memory.

Table 4.4 Physical Address and Cache Attributes for dseg, dmseg, and drseg Address Spaces

| Segment Name | Sub-Segment Name | Virtual Address | Generates Physical Address | Cache Attribute |
|--------------|------------------|---------------------------------|--|-----------------|
| dseg | dmseg | 0xFF20_0000 through 0xFF2F_FFFF | dmseg maps to addresses 0x0_0000 - 0xF_FFFF in EJTAG probe memory space. | Uncached |
| | drseg | 0xFF30_0000 through 0xFF3F_FFFF | drseg maps to the breakpoint registers 0x0_0000 - 0xF_FFFF | |

4.2.5.1 Conditions and Behavior for Access to drseg, EJTAG Registers

The behavior of access to the drseg address range at 0xFF30_0000 to 0xFF3F_FFFF is determined as shown in [Table 4.5](#)

Table 4.5 Accesses to drseg Address Range

| Transaction | LSNM bit in Debug Register | Access |
|--------------|----------------------------|-----------------------------------|
| Load / Store | 1 | Kernel mode address space (kseg3) |
| Fetch | Don't care | drseg, see comments below |
| Load / Store | 0 | |

Debug software is expected to read the debug control register (*DCR*) to determine which other memory mapped registers exist in drseg. The value returned in response to a read of any unimplemented memory mapped register is unpredictable, and writes are ignored to any unimplemented register in the drseg. Refer to [Chapter 11, “EJTAG Debug Support in the 24K® Core” on page 240](#) for more information on the DCR.

The allowed access size is limited for the drseg. Only word size transactions are allowed. Operation of the processor is undefined for other transaction sizes.

4.2.5.2 Conditions and Behavior for Access to dmseg, EJTAG Memory

The behavior of access to the dmseg address range at 0xFF20_0000 to 0xFF2F_FFFF is determined by the table shown in [Table 4.6](#).

Table 4.6 Accesses to dmseg Address Range

| Transaction | ProbEn bit in DCR Register | LSNM bit in Debug Register | Access |
|--------------|----------------------------|----------------------------|-----------------------------------|
| Load / Store | Don't care | 1 | Kernel mode address space (kseg3) |
| Fetch | 1 | Don't care | dmseg |
| Load / Store | 1 | 0 | |
| Fetch | 0 | Don't care | See comments below |
| Load / Store | 0 | 0 | |

The case with access to the dmseg when the *ProbEn* bit in the *DCR* register is 0 is not expected to happen. Debug software is expected to check the state of the *ProbEn* bit in *DCR* register before attempting to reference dmseg. If such a reference does happen, the reference hangs until it is satisfied by the probe. The probe can not assume that there will never be a reference to dmseg if the *ProbEn* bit in the *DCR* register is 0 because there is an inherent race between the debug software sampling the *ProbEn* bit as 1 and the probe clearing it to 0.

4.3 Translation Lookaside Buffer

The following subsections discuss the TLB memory management scheme used in the 24Kc processor core. The TLB consists of the joint and micro address translation buffers:

- 16-64 dual-entry fully associative Joint TLB (JTLB)
- 4-entry fully associative Instruction micro TLB (ITLB)
- 8-entry fully associative Data micro TLB (DTLB)

4.3.1 Joint TLB

The 16-64 dual-entry, fully associative Joint TLB maps 32-128 virtual pages to their corresponding physical addresses. The purpose of the TLB is to translate virtual addresses and their corresponding ASID into a physical memory address. The translation is performed by comparing the upper bits of the virtual address (along with the ASID bits) against each of the entries in the *tag* portion of the JTLB structure. Because this structure is used to translate both instruction and data virtual addresses, it is referred to as a “joint” TLB.

The JTLB is organized as 16-64 pairs of even and odd entries containing descriptions of pages that range in size from 4-KBytes to 256MBytes into the 4-GByte physical address space.

The JTLB is organized in pairs of page entries to minimize its overall size. Each virtual *tag* entry corresponds to two physical data entries, an even page entry and an odd page entry. The highest order virtual address bit not participating in the tag comparison is used to determine which of the two data entries is used. Since page size can vary on a page-pair basis, the determination of which address bits participate in the comparison and which bit is used to make the even-odd selection must be done dynamically during the TLB lookup.

Figure 4.8 shows the contents of one of the dual-entries in the JTLB. The bit range indication in the figure serves to clarify which address bits are (or may be) affected during the translation process.

Figure 4.8 JTLB Entry (Tag and Data)

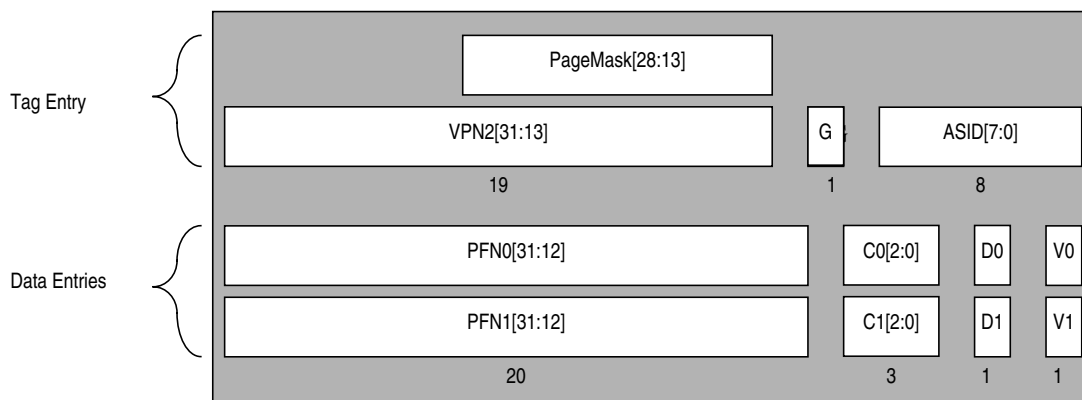


Table 4.7 and Table 4.8 explain each of the fields in a JTLB entry.

Table 4.7 TLB Tag Entry Fields

| Field Name | Description | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----------------------|---|--------------------------|-----------|--------------------------|----------------------|-----|-----------|----------------------|------|-----------|----------------------|------|-----------|----------------------|-------|-----------|----------------------|-----|-----------|----------------------|-----|-----------|----------------------|------|-----------|----------------------|------|-----------|----------------------|-------|-----------|
| PageMask[28:13] | <p>Page Mask Value. The Page Mask defines the page size by masking the appropriate VPN2 bits from being involved in a comparison. It is also used to determine which address bit is used to make the even-odd page (PFN0-PFN1) determination. See the table below.</p> <table><tr><th>PageMask</th><th>Page Size</th><th>Even/Odd Bank Select Bit</th></tr><tr><td>00_0000_0000_0000_00</td><td>4KB</td><td>VAddr[12]</td></tr><tr><td>00_0000_0000_0000_11</td><td>16KB</td><td>VAddr[14]</td></tr><tr><td>00_0000_0000_0011_11</td><td>64KB</td><td>VAddr[16]</td></tr><tr><td>00_0000_0000_1111_11</td><td>256KB</td><td>VAddr[18]</td></tr><tr><td>00_0000_0011_1111_11</td><td>1MB</td><td>VAddr[20]</td></tr><tr><td>00_0000_1111_1111_11</td><td>4MB</td><td>VAddr[22]</td></tr><tr><td>00_0011_1111_1111_11</td><td>16MB</td><td>VAddr[24]</td></tr><tr><td>00_1111_1111_1111_11</td><td>64MB</td><td>VAddr[26]</td></tr><tr><td>11_1111_1111_1111_11</td><td>256MB</td><td>VAddr[28]</td></tr></table> <p>The PageMask column above shows all the legal values for PageMask. Because each pair of bits can only have the same value, the physical entry in the JTLB will only save a compressed version of the PageMask using only 8 bits. This is however transparent to software, which will always work with a 16 bit field</p> | PageMask | Page Size | Even/Odd Bank Select Bit | 00_0000_0000_0000_00 | 4KB | VAddr[12] | 00_0000_0000_0000_11 | 16KB | VAddr[14] | 00_0000_0000_0011_11 | 64KB | VAddr[16] | 00_0000_0000_1111_11 | 256KB | VAddr[18] | 00_0000_0011_1111_11 | 1MB | VAddr[20] | 00_0000_1111_1111_11 | 4MB | VAddr[22] | 00_0011_1111_1111_11 | 16MB | VAddr[24] | 00_1111_1111_1111_11 | 64MB | VAddr[26] | 11_1111_1111_1111_11 | 256MB | VAddr[28] |
| PageMask | Page Size | Even/Odd Bank Select Bit | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_0000_0000_00 | 4KB | VAddr[12] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_0000_0000_11 | 16KB | VAddr[14] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_0000_0011_11 | 64KB | VAddr[16] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_0000_1111_11 | 256KB | VAddr[18] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_0011_1111_11 | 1MB | VAddr[20] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0000_1111_1111_11 | 4MB | VAddr[22] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_0011_1111_1111_11 | 16MB | VAddr[24] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00_1111_1111_1111_11 | 64MB | VAddr[26] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11_1111_1111_1111_11 | 256MB | VAddr[28] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| VPN2[31:13] | Virtual Page Number divided by 2. This field contains the upper bits of the virtual page number. Because it represents a pair of TLB pages, it is divided by 2. Bits 31:29 are always included in the TLB lookup comparison. Bits 28:13 are included depending on the page size, defined by PageMask | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G | Global Bit. When set, indicates that this entry is global to all processes and/or threads and thus disables inclusion of the ASID in the comparison. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ASID[7:0] | Address Space Identifier. Identifies which process or thread this TLB entry is associated with. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Table 4.8 TLB Data Entry Fields

| Field Name | Description |
|-----------------------------|--|
| PFN0[31:12], PFN1[31:12] | Physical Frame Number. Defines the upper bits of the physical address. |

Table 4.8 TLB Data Entry Fields (Continued)

| Field Name | Description | | | | | | | | | | | | | | |
|---------------------|---|--------|---------------------|---|--|---|----------|---|----------|---|--|-------|----------|---|----------------------|
| C0[2:0], C1[2:0] | <p>Cacheability. Contains an encoded value of the cacheability attributes and determines whether the page should be placed in the cache or not. The field is encoded as follows:</p> <table> <tr> <th>C[2:0]</th><th>Coherency Attribute</th></tr> <tr> <td>0</td><td>Cacheable, noncoherent, write-through, no write allocate</td></tr> <tr> <td>1</td><td>Reserved</td></tr> <tr> <td>2</td><td>Uncached</td></tr> <tr> <td>3</td><td>Cacheable, noncoherent, write-back, write allocate</td></tr> <tr> <td>4,5,6</td><td>Reserved</td></tr> <tr> <td>7</td><td>Uncached Accelerated</td></tr> </table> | C[2:0] | Coherency Attribute | 0 | Cacheable, noncoherent, write-through, no write allocate | 1 | Reserved | 2 | Uncached | 3 | Cacheable, noncoherent, write-back, write allocate | 4,5,6 | Reserved | 7 | Uncached Accelerated |
| C[2:0] | Coherency Attribute | | | | | | | | | | | | | | |
| 0 | Cacheable, noncoherent, write-through, no write allocate | | | | | | | | | | | | | | |
| 1 | Reserved | | | | | | | | | | | | | | |
| 2 | Uncached | | | | | | | | | | | | | | |
| 3 | Cacheable, noncoherent, write-back, write allocate | | | | | | | | | | | | | | |
| 4,5,6 | Reserved | | | | | | | | | | | | | | |
| 7 | Uncached Accelerated | | | | | | | | | | | | | | |
| D0, D1 | “Dirty” or Write-enable Bit. Indicates that the page has been written and/or is writable. If this bit is set, stores to the page are permitted. If the bit is cleared, stores to the page cause a TLB Modified exception. | | | | | | | | | | | | | | |
| V0, V1 | Valid Bit. Indicates that the TLB entry and, thus, the virtual page mapping are valid. If this bit is set, accesses to the page are permitted. If the bit is cleared, accesses to the page cause a TLB Invalid exception. | | | | | | | | | | | | | | |

In order to fill an entry in the JTLB, software executes a TLBWI or TLBWR instruction (See [Section 4.4.3 “TLB Instructions”](#)). Prior to invoking one of these instructions, several CP0 registers must be updated with the information to be written to a TLB entry:

- PageMask is set in the CP0 *PageMask* register.
- *VPN2*, and *ASID* are set in the CP0 *EntryHi* register.
- *PFN0*, *C0*, *D0*, *V0*, and *G* bits are set in the CP0 *EntryLo0* register.
- *PFN1*, *C1*, *D1*, *V1*, and *G* bits are set in the CP0 *EntryLo1* register.

Note that the global bit “G” is part of both *EntryLo0* and *EntryLo1*. The resulting “G” bit in the JTLB entry is the logical AND between the two fields in *EntryLo0* and *EntryLo1*. Please refer to [Chapter 6, “CP0 Registers of the 24K® Core”](#) on page 146 for further details.

The address space identifier (ASID) helps to reduce the frequency of TLB flushing on a context switch. The existence of the ASID allows multiple processes to exist in both the TLB and instruction caches. The ASID value is stored in the *EntryHi* register and is compared to the ASID value of each entry.

4.3.2 Instruction TLB

The ITLB is a small, 4-entry fully associative TLB dedicated to perform translations for the instruction stream. The ITLB only maps 4-Kbyte pages/sub-pages or 1-Mbyte pages/sub-pages.

The ITLB is managed by hardware and is transparent to software. If a fetch address cannot be translated by the ITLB, the JTLB is accessed trying to translate it in the following clock cycles. If successful, the translation information is copied into the ITLB and bypassed to the tag comparators. This results in an ITLB miss penalty of at least 2 cycles. Depending on the JTLB implementation or if it is busy with other operations, it may take additional cycles.

4.3.3 Data TLB

The DTLB is a small 8-entry, fully associative TLB which provides a faster translation for Load/Store addresses than is possible with the JTLB. The DTLB only maps 4-Kbyte pages/sub-pages or 1-Mbyte pages/sub-pages.

Like the ITLB, the DTLB is managed by hardware and is transparent to software. For simultaneous ITLB and DTLB misses, the DTLB has priority and will access the JTLB first.

4.4 Virtual-to-Physical Address Translation

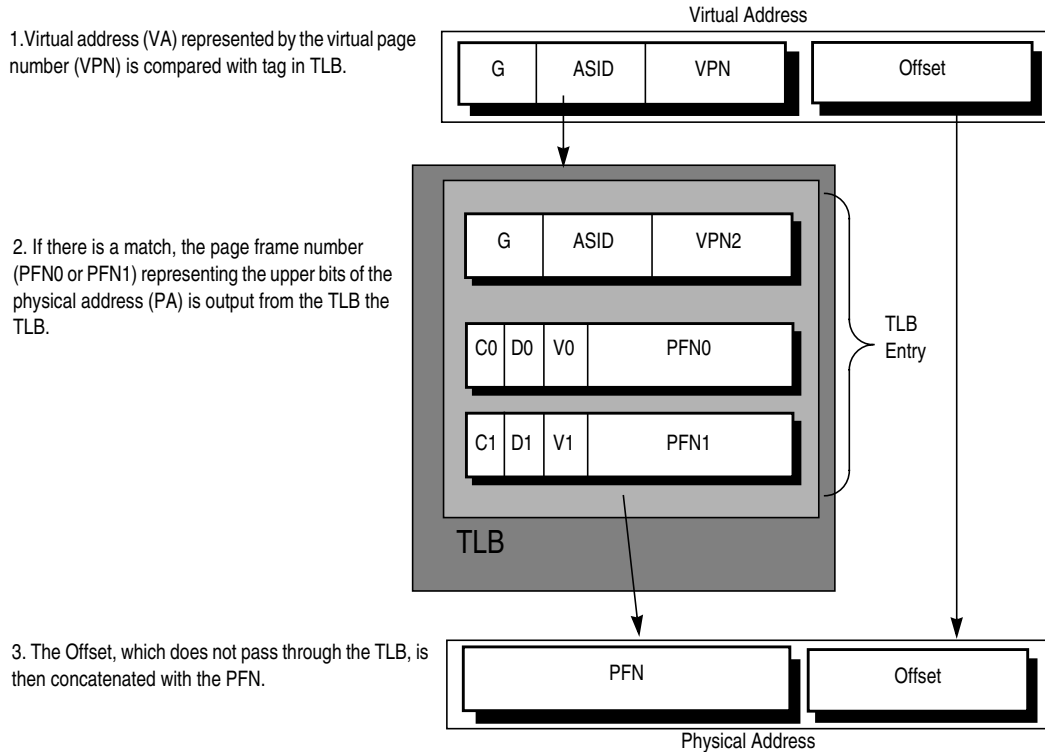
Converting a virtual address to a physical address begins by comparing the virtual address from the processor with the virtual addresses in the TLB. There is a match when the VPN of the address is the same as the VPN field of the entry, and either:

- The Global (G) bit of both the even and odd pages of the TLB entry are set, or
- The ASID field of the virtual address is the same as the ASID field of the TLB entry

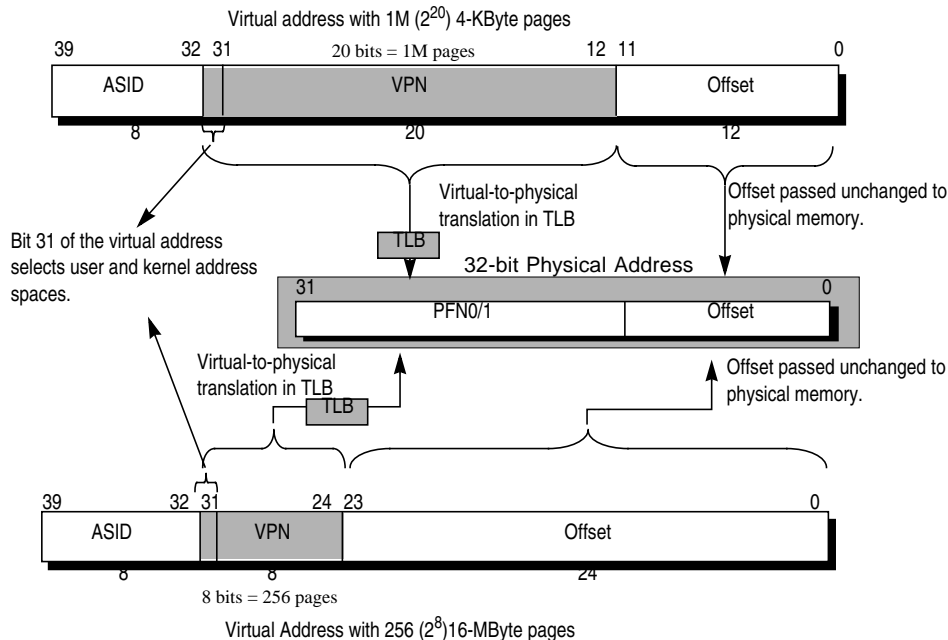
This match is referred to as a TLB *hit*. If there is no match, a TLB *miss* exception is taken by the processor and software is allowed to refill the TLB from a page table of virtual/physical addresses in memory.

Figure 4.9 shows the logical translation of a virtual address into a physical address.

In this figure the virtual address is extended with an 8-bit ASID, which reduces the frequency of TLB flushing during a context switch. This 8-bit ASID contains the number assigned to that process and is stored in the CP0 *EntryHi* register.

Figure 4.9 Overview of a Virtual-to-Physical Address Translation

If there is a virtual address match in the TLB, the Physical Frame Number (PFN) is output from the TLB and concatenated with the *Offset*, to form the physical address. The *Offset* represents an address within the page frame space. As shown in [Figure 4.9](#), the *Offset* does not pass through the TLB. [Figure 4.10](#) shows a flow diagram of the address translation process for two page sizes. The top portion of the figure shows a virtual address for a 4 KByte page size. The width of the *Offset* is defined by the page size. The remaining 20 bits of the address represent the virtual page number (VPN). The bottom portion of [Figure 4.10](#) shows the virtual address for a 16 MByte page size. The remaining 8 bits of the address represent the VPN.

Figure 4.10 32-bit Virtual Address Translation

4.4.1 Hits, Misses, and Multiple Matches

Each JTLB entry contains a tag and two data fields. If a match is found, the upper bits of the virtual address are replaced with the page frame number (PFN) stored in the corresponding entry in the data array of the JTLB. The granularity of JTLB mappings is defined in terms of TLB pages. The JTLB supports pages of different sizes ranging from 4KB to 256 MB in powers of 4. If a match is found, but the entry is invalid (i.e., the V bit in the data field is 0), a TLB Invalid exception is taken.

If no match occurs (TLB miss), an exception is taken and software refills the TLB from the page table resident in memory. [Figure 4.11](#) shows the translation and exception flow of the TLB.

Software can write over a selected TLB entry or use a hardware mechanism to write into a random entry. The *Random* register selects which TLB entry to use on a TLBWR. This register decrements almost every cycle, wrapping to the maximum once its value is equal to the *Wired* register. Thus, TLB entries below the *Wired* value cannot be replaced by a TLBWR allowing important mappings to be preserved. In order to reduce the possibility for a livelock situation, the *Random* register includes a 10-bit LFSR that introduces a pseudo-random perturbation into the decrement.

The core implements a TLB write-compare mechanism to ensure that multiple TLB matches do not occur. On the TLB write operation, the *VPN2* field to be written is compared with all other entries in the TLB. If a match occurs, the entry in the TLB is valid, and the entry being written is valid, the core takes a machine-check exception, sets the *TS* bit in the CP0 *Status* register, and aborts the write operation. For further details on exceptions, please refer to [Chapter 5, “Exceptions and Interrupts in the 24K® Core”](#) on page 110. There is a hidden bit in each TLB entry that is cleared on a Reset. This bit is set once the TLB entry is written and is included in the match detection. Therefore, uninitialized TLB entries will not cause a TLB shutdown.

Compared with previous cores from MIPS Technologies, the 24K core uses a more relaxed check for multiple matches in order to avoid machine check exceptions while flushing or initializing the TLB. On a write, all matching entries are disabled to prevent them from matching on future compares. A machine check is only signaled if the entry

being written has its valid bit set, the matching entry in the TLB has its valid bit set, and the matching entry is not the entry being written. The cases for the signalling of the machine check exception are enumerated in [Table 4.9](#).

Table 4.9 Machine Check Exception

| Existing Match | Matching Entry equals Written Entry | Existing Page Valid Bit | Written Page Valid Bit | Machine Check? |
|----------------|-------------------------------------|-------------------------|------------------------|----------------|
| No | X | X | X | No |
| Yes | Yes | X | X | No |
| Yes | No | 0 | 0 | No |
| Yes | No | 0 | 1 | No |
| Yes | No | 1 | 0 | No |
| Yes | No | 1 | 1 | Yes |

4.4.2 Memory Space

To assist in controlling both the amount of mapped space and the replacement characteristics of various memory regions, the 24K core provides two mechanisms.

4.4.2.1 Page Sizes

First, the page size can be configured, on a per entry basis, to map different page sizes ranging from 4 KByte to 256 MByte, in multiples of 4. The CP0 *PageMask* register is loaded with the desired page size, which is then entered into the TLB when a new entry is written. Thus, operating systems can provide special-purpose maps. For example, a typical frame buffer can be memory mapped with only one TLB entry.

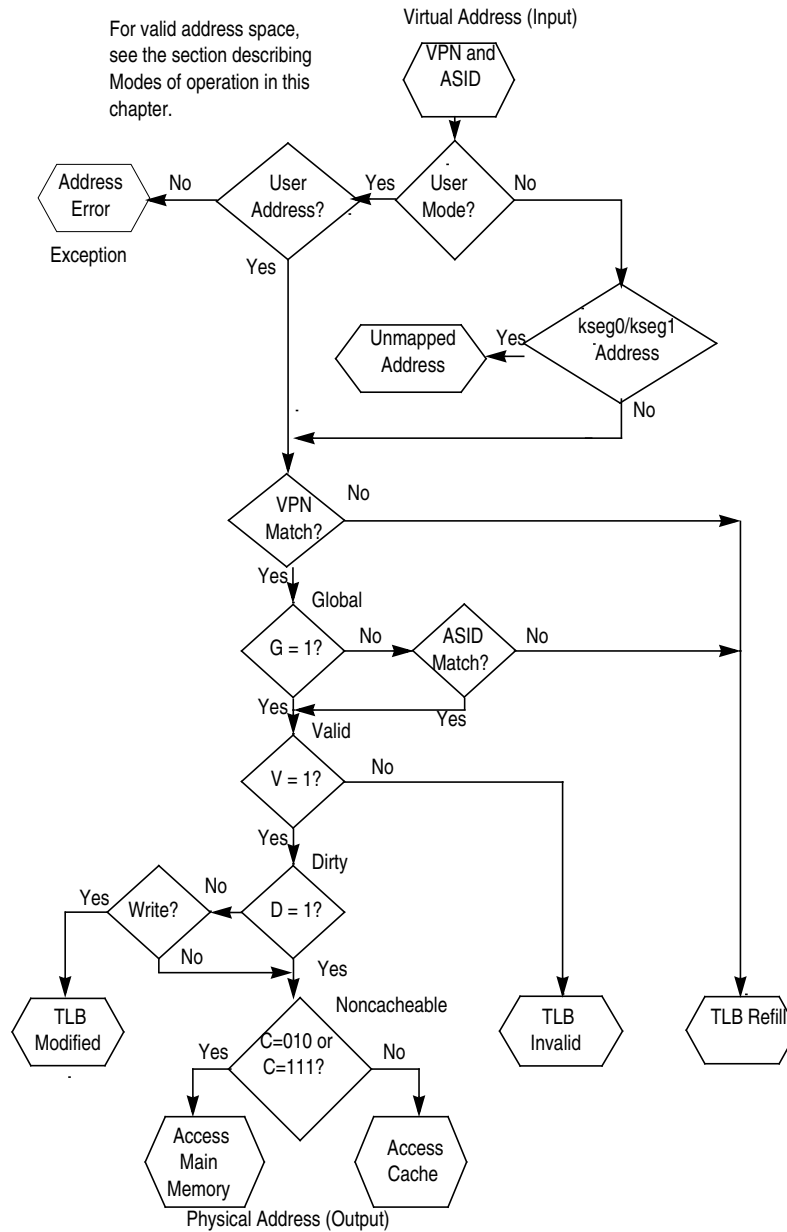
The 24K core implements the following page sizes:

4K, 16K, 64K, 256K, 1M, 4M, 16M, 64M, 256M.

Software may determine which page sizes are supported by writing all ones to the CP0 *PageMask* register, then reading the value back. For additional information, see [Section 6.2.5 “UserLocal Register \(CP0 Register 4, Select 2\)”](#).

4.4.2.2 Replacement Algorithm

The second mechanism controls the replacement algorithm when a TLB miss occurs. To select a TLB entry to be written with a new mapping, the 24K core provides a random replacement algorithm. However, the processor also provides a mechanism whereby a programmable number of mappings can be locked into the TLB via the CP0 *Wired* register, thus avoiding random replacement. Please refer to [Section 6.2.7 “Wired Register \(CP0 Register 6, Select 0\)”](#) for further details.

Figure 4.11 TLB Address Translation Flow in the 24K® Processor Core

4.4.3 TLB Instructions

Table 4.10 lists the TLB-related instructions. Refer to [Chapter 12, “24K® Processor Core Instructions”](#) on page 303 for more information on these instructions.

Table 4.10 TLB Instructions

| Op Code | Description of Instruction |
|---------|------------------------------------|
| TLBP | Translation Lookaside Buffer Probe |
| TLBR | Translation Lookaside Buffer Read |

Table 4.10 TLB Instructions (Continued)

| Op Code | Description of Instruction |
|---------|---|
| TLBWI | Translation Lookaside Buffer Write Index |
| TLBWR | Translation Lookaside Buffer Write Random |

4.5 Fixed Mapping MMU

The 24K core optionally implements a simple Fixed Mapping (FM) memory management unit that is smaller than the a full translation lookaside buffer (TLB) and more easily synthesized. Like a TLB, the FM performs virtual-to-physical address translation and provides attributes for the different memory segments. Those memory segments which are unmapped in a TLB implementation (kseg0 and kseg1) are translated identically by the FM MMU.

The FM also determines the cacheability of each segment. These attributes are controlled via bits in the *Config* register. Table 4.11 shows the encoding for the *K23* (bits 30:28), *KU* (bits 27:25) and *K0* (bits 2:0) of the *Config* register.

Table 4.11 Cache Coherency Attributes

| Config Register Fields K23, KU, and K0 | Cache Coherency Attribute |
|---|--|
| 0 | Cacheable, noncoherent, write-through, no write allocate |
| 1 | Reserved |
| 2 | Uncached |
| 3 | Cacheable, noncoherent, write-back, write allocate |
| 4,5,6 | Reserved |
| 7 | Uncached Accelerated |

With the FM MMU, no translation exceptions can be taken, although address errors are still possible.

Table 4.12 Cacheability of Segments with Fixed Mapping Translation

| Segment | Virtual Address Range | Cacheability |
|------------|-------------------------|--|
| useg/kuseg | 0x0000_0000-0x7FFF_FFFF | Controlled by the <i>KU</i> field (bits 27:25) of the <i>Config</i> register. Refer to Table 4.11 for the encoding. |
| kseg0 | 0x8000_0000-0x9FFF_FFFF | Controlled by the <i>K0</i> field (bits 2:0) of the <i>Config</i> register. See Table 4.11 for the encoding. |
| kseg1 | 0xA000_0000-0xBFFF_FFFF | Always uncacheable |
| kseg2 | 0xC000_0000-0xDFFF_FFFF | Controlled by the <i>K23</i> field (bits 30:28) of the <i>Config</i> register. Refer to Table 4.11 for the encoding. |
| kseg3 | 0xE000_0000-0xFFFF_FFFF | Controlled by <i>K23</i> field (bits 30:28) of the <i>Config</i> register. Refer to Table 4.11 for the encoding. |

The FM performs a simple translation to map from virtual addresses to physical addresses. This mapping is shown in Figure 4.12. When *ERL*=1, useg and kuseg become unmapped and uncached just like they do if there is a TLB. The *ERL* mapping is shown in Figure 4.13.

The *ERL* bit is usually never asserted by software. It is asserted by hardware after a Reset, NMI, or Cache Error. See [Section 5.8 “Exceptions”](#) for further information on exceptions.

Figure 4.12 FM Memory Map (ERL=0) in the 24K® Processor Core

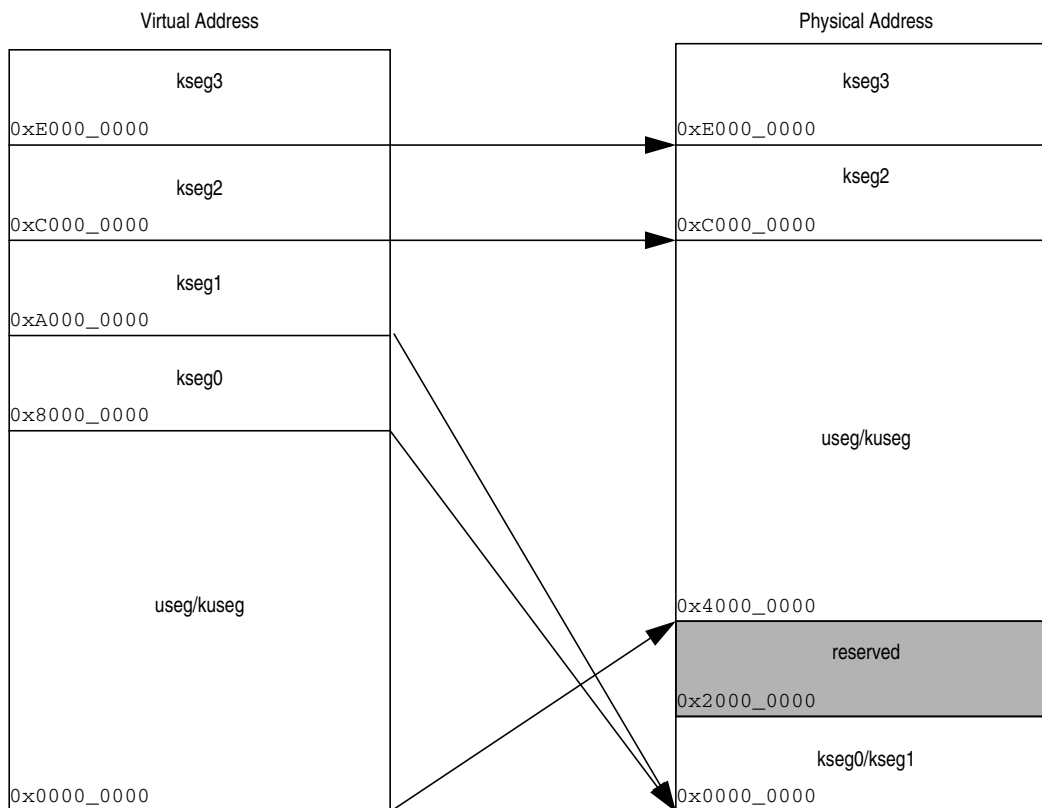
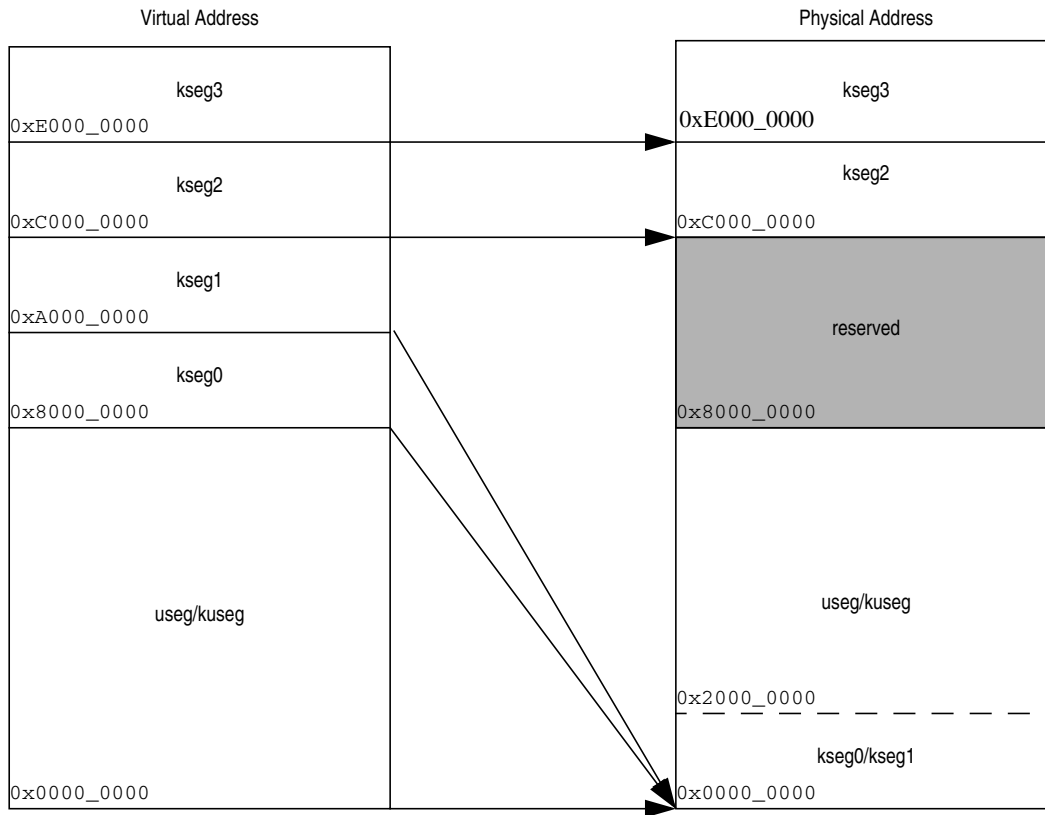


Figure 4.13 FM Memory Map (ERL=1) in the 24K® Processor Core

4.6 System Control Coprocessor

The System Control Coprocessor (CP0) is implemented as an integral part of the 24K processor core and supports memory management, address translation, exception handling, and other privileged operations. Certain CP0 registers are used to support memory management. Refer to [Chapter 6, “CP0 Registers of the 24K® Core”](#) on page 146 for more information on the CP0 register set.

Exceptions and Interrupts in the 24K® Core

Programs executing on the 24K processor core receive exceptions from a number of sources, including translation lookaside buffer (TLB) misses, arithmetic overflows, I/O interrupts, and system calls. When one of these exceptions is detected, the normal sequence of instruction execution is suspended and the processor enters kernel mode.

In kernel mode interrupts are disabled and a software exception processor (also called a handler), located at a specific address, is executed. The handler saves the context of the processor, including the contents of the program counter, the current operating mode, and the status of the interrupts (enabled or disabled). This context is saved so it can be restored when the exception has been serviced.

When an exception occurs, the *Exception Program Counter (EPC)* register is loaded with a location where execution can restart after the exception has been serviced. Most exceptions are *precise*, which mean that *EPC* can be used to identify the instruction that caused the exception. For precise exceptions the restart location in the *EPC* register is the address of the instruction that caused the exception or, if the instruction was executing in a branch delay slot, the address of the branch instruction immediately preceding the delay slot. To distinguish between the two, software must read the BD bit in the CP0 *Cause* register. Bus error exceptions and CP2 exceptions may be imprecise. For imprecise exceptions the instruction that caused the exception can not be identified.

This chapter contains the following sections:

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- [Section 5.4 “GPR Shadow Registers”](#)
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5.1 Exception Conditions

When an exception condition occurs, the relevant instruction and all those that follow it in the pipeline are cancelled. Accordingly, any stall conditions and any later exception conditions that may have referenced this instruction are inhibited; there is no benefit in servicing stalls for a cancelled instruction.

When an exception condition is detected on an instruction fetch, the core aborts that instruction and all instructions that follow. When this instruction reaches the WB stage, the exception flag causes it to write various CP0 registers with the exception state, change the current program counter (PC) to the appropriate exception vector address, and clear the exception bits of earlier pipeline stages.

For most exception types this implementation allows all preceding instructions to complete execution and prevents all subsequent instructions from completing. Thus, the value in the *EPC* (*ErrorEPC* for errors, or *DEPC* for debug exceptions) is sufficient to restart execution. It also ensures that exceptions are taken in the order of execution; an instruction taking an exception may itself be killed by an instruction further down the pipeline that takes an exception in a later cycle.

A number of exceptions can be taken imprecisely - that is, they are taken after the instruction that caused them has completed and potentially after following instructions have completed.

5.2 Exception Priority

Table 5.1 lists all possible exceptions, and the relative priority of each, highest to lowest. Several of these exceptions can happen simultaneously, in that event the exception with the highest priority is the one taken.

Table 5.1 Priority of Exceptions

| Exception | Description |
|-------------------|---|
| Reset | Assertion of SI_Reset signal. |
| DSS | EJTAG Debug Single Step. |
| DINT | EJTAG Debug Interrupt. Caused by the assertion of the external <i>EJ_DINT</i> input, or by setting the EjtagBrk bit in the <i>ECR</i> register. |
| DDBLImpr/DDBSImpr | Debug Data Break Load/Store Imprecise |
| NMI | Asserting edge of <i>SI_NMI</i> signal. |
| Machine Check | TLB write that conflicts with an existing entry. |
| Interrupt | Assertion of unmasked hardware or software interrupt signal. |
| Deferred Watch | Deferred Watch (unmasked by K DM->!(K DM) transition). |
| DIB | EJTAG debug hardware instruction break matched. |
| WATCH | A reference to an address in one of the watch registers (fetch). |
| AdEL | Fetch address alignment error. Fetch reference to protected address. |
| TLBL | Fetch TLB miss Fetch TLB hit to page with V=0 |
| ICache Error | Parity error on ICache access |
| IBE | Instruction fetch bus error. |
| DBp | EJTAG Breakpoint (execution of SDBBP instruction). |
| Sys | Execution of SYSCALL instruction. |
| Bp | Execution of BREAK instruction. |
| CpU | Execution of a coprocessor instruction for a coprocessor that is not enabled. |
| CEU | Execution of a CorExtend instruction modifying local state when CorExtend is not enabled. |
| RI | Execution of a Reserved Instruction. |

Table 5.1 Priority of Exceptions (Continued)

| Exception | Description |
|----------------|---|
| FPE | Floating Point exception |
| C2E | Coprocessor2 Exception |
| IS1 | Implementation specific Coprocessor2 exception |
| Ov | Execution of an arithmetic instruction that overflowed. |
| Tr | Execution of a trap (when trap condition is true). |
| DDBL / DDBS | EJTAG Data Address Break (address only) |
| WATCH | A reference to an address in one of the watch registers (data). |
| AdEL | Load address alignment error. Load reference to protected address. |
| AdES | Store address alignment error. Store to protected address. |
| TLBL | Load TLB miss. Load TLB hit to page with V=0 |
| TLBS | Store TLB miss. Store TLB hit to page with V=0 |
| TLB Mod | Store to TLB page with D=0. |
| DCache Error | Cache parity error - imprecise |
| L2 Cache Error | L2 Cache ECC error - imprecise |
| DBE | Load or store bus error - imprecise |

5.3 Interrupts

Older 32-bit cores available from MIPS that implemented Release 1 of the Architecture included support for two software interrupts, six hardware interrupts, and a special-purpose timer interrupt. The timer interrupt was provided external to the core and typically combined with hardware interrupt 5 in an system-dependent manner. Interrupts were handled either through the general exception vector (offset 16#180) or the special interrupt vector (16#200), based on the value of Cause_{IV}. Software was required to prioritize interrupts as a function of the Cause_{IP} bits in the interrupt handler prologue.

Release 2 of the Architecture, implemented by the 24K core, adds an upward-compatible extension to the Release 1 interrupt architecture that supports vectored interrupts. In addition, Release 2 adds a new interrupt mode that supports the use of an external interrupt controller by changing the interrupt architecture.

Additionally, internal performance counters were added to the 24K core. These counters can be set up to count various events within the core. When the MSB of the counter gets set, it can trigger a performance counter interrupt. This is handled like the timer interrupt - it is an output of the core and can be brought back into the core's interrupt pins in a system dependent manner.

5.3.1 Interrupt Modes

The 24K core includes support for three interrupt modes, as defined by Release 2 of the Architecture:

- Interrupt compatibility mode, which acts identically to that in an implementation of Release 1 of the Architecture.

- Vectored Interrupt (VI) mode, which adds the ability to prioritize and vector interrupts to a handler dedicated to that interrupt, and to assign a GPR shadow set for use during interrupt processing. The presence of this mode is denoted by the `VInt` bit in the `Config3` register. This mode is architecturally optional; but it is always present on the 24K core, so the `VInt` bit will always read as a 1 for the 24K core.
- External Interrupt Controller (EIC) mode, which redefines the way in which interrupts are handled to provide full support for an external interrupt controller handling prioritization and vectoring of interrupts. This presence of this mode denoted by the `VEIC` bit in the `Config3` register. Again, this mode is architecturally optional. On the 24K core, the `VEIC` bit is set externally by the static input, `SI_EICPresent`, to allow system logic to indicate the presence of an external interrupt controller.

The reset state of the processor is to interrupt compatibility mode such that a processor supporting Release 2 of the Architecture, like the 24K core, is fully compatible with implementations of Release 1 of the Architecture.

Table 5.2 shows the current interrupt mode of the processor as a function of the coprocessor 0 register fields that can affect the mode.

Table 5.2 Interrupt Modes

| <code>Status_{BEV}</code> | <code>Cause_{IV}</code> | <code>IntCtl_{VS}</code> | <code>Config3_{VINT}</code> | <code>Config3_{VEIC}</code> | Interrupt Mode |
|-----------------------------------|---------------------------------|----------------------------------|-------------------------------------|-------------------------------------|--|
| 1 | x | x | x | x | Compatibility |
| x | 0 | x | x | x | Compatibility |
| x | x | =0 | x | x | Compatibility |
| 0 | 1 | ≠0 | 1 | 0 | Vectored Interrupt |
| 0 | 1 | ≠0 | x | 1 | External Interrupt Controller |
| 0 | 1 | ≠0 | 0 | 0 | Can't happen - <code>IntCtl_{VS}</code> can not be non-zero if neither Vectored Interrupt nor External Interrupt Controller mode is implemented. |
| "x" denotes don't care | | | | | |

5.3.1.1 Interrupt Compatibility Mode

This is the default interrupt mode for the processor and is entered when a Reset exception occurs. In this mode, interrupts are non-vectored and dispatched through exception vector offset 16#180 (if `CauseIV` = 0) or vector offset 16#200 (if `CauseIV` = 1). This mode is in effect if any of the following conditions are true:

- `CauseIV` = 0
- `StatusBEV` = 1
- `IntCtlVS` = 0, which would be the case if vectored interrupts are not implemented, or have been disabled.

A typical software handler for interrupt compatibility mode might look as follows:

```
/*
 * Assumptions:
 * - CauseIV = 1 (if it were zero, the interrupt exception would have to
```

```

*           be isolated from the general exception vector before getting
*           here)
* - GPRs k0 and k1 are available (no shadow register switches invoked in
*                               compatibility mode)
* - The software priority is IP7..IP0 (HW5..HW0, SW1..SW0)
*
* Location: Offset 0x200 from exception base
*/

IVexception:
    mfc0    k0, C0_Cause      /* Read Cause register for IP bits */
    mfc0    k1, C0_Status    /* and Status register for IM bits */
    andi    k0, k0, M_CauseIM /* Keep only IP bits from Cause */
    and     k0, k0, k1       /* and mask with IM bits */
    beq     k0, zero, Dismiss /* no bits set - spurious interrupt */
    clz     k0, k0           /* Find first bit set, IP7..IP0; k0 = 16..23 */
    xori    k0, k0, 0x17     /* 16..23 => 7..0 */
    sll     k0, k0, VS       /* Shift to emulate software IntCtlVS */
    la      k1, VectorBase   /* Get base of 8 interrupt vectors */
    addu    k0, k0, k1       /* Compute target from base and offset */
    jr      k0               /* Jump to specific exception routine */
    nop

/*
* Each interrupt processing routine processes a specific interrupt, analogous
* to those reached in VI or EIC interrupt mode. Since each processing routine
* is dedicated to a particular interrupt line, it has the context to know
* which line was asserted. Each processing routine may need to look further
* to determine the actual source of the interrupt if multiple interrupt requests
* are ORed together on a single IP line. Once that task is performed, the
* interrupt may be processed in one of two ways:
*
* - Completely at interrupt level (e.g., a simply UART interrupt). The
*   SimpleInterrupt routine below is an example of this type.
* - By saving sufficient state and re-enabling other interrupts. In this
*   case the software model determines which interrupts are disabled during
*   the processing of this interrupt. Typically, this is either the single
*   StatusIM bit that corresponds to the interrupt being processed, or some
*   collection of other StatusIM bits so that "lower" priority interrupts are
*   also disabled. The NestedInterrupt routine below is an example of this type.
*/

SimpleInterrupt:
/*
* Process the device interrupt here and clear the interrupt request
* at the device. In order to do this, some registers may need to be
* saved and restored. The coprocessor 0 state is such that an ERET
* will simply return to the interrupted code.
*/
    eret                    /* Return to interrupted code */

NestedException:
/*
* Nested exceptions typically require saving the EPC and Status registers,
* any GPRs that may be modified by the nested exception routine, disabling
* the appropriate IM bits in Status to prevent an interrupt loop, putting
* the processor in kernel mode, and re-enabling interrupts. The sample code
* below can not cover all nuances of this processing and is intended only

```

```

* to demonstrate the concepts.
*/

/* Save GPRs here, and setup software context */
mfc0    k0, C0_EPC          /* Get restart address */
sw      k0, EPCSave         /* Save in memory */
mfc0    k0, C0_Status       /* Get Status value */
sw      k0, StatusSave      /* Save in memory */
li      k1, ~IMbitsToClear  /* Get Im bits to clear for this interrupt */
/*      this must include at least the IM bit */
/*      for the current interrupt, and may include */
/*      others */
and     k0, k0, k1          /* Clear bits in copy of Status */
ins     k0, zero, S_StatusEXL, (W_StatusKSU+W_StatusERL+W_StatusEXL)
/* Clear KSU, ERL, EXL bits in k0 */
mtc0    k0, C0_Status       /* Modify mask, switch to kernel mode, */
/*      re-enable interrupts */

/*
* Process interrupt here, including clearing device interrupt.
* In some environments this may be done with a thread running in
* kernel or user mode. Such an environment is well beyond the scope of
* this example.
*/

/*
* To complete interrupt processing, the saved values must be restored
* and the original interrupted code restarted.
*/

di      /* Disable interrupts - may not be required */
lw      k0, StatusSave      /* Get saved Status (including EXL set) */
lw      k1, EPCSave         /* and EPC */
mtc0    k0, C0_Status       /* Restore the original value */
mtc0    k1, C0_EPC         /* and EPC */
/* Restore GPRs and software state */
eret    /* Dismiss the interrupt */

```

5.3.1.2 Vectored Interrupt Mode

Vectored Interrupt mode builds on the interrupt compatibility mode by adding a priority encoder to prioritize pending interrupts and to generate a vector with which each interrupt can be directed to a dedicated handler routine. This mode also allows each interrupt to be mapped to a GPR shadow set for use by the interrupt handler. Vectored Interrupt mode is in effect if all of the following conditions are true:

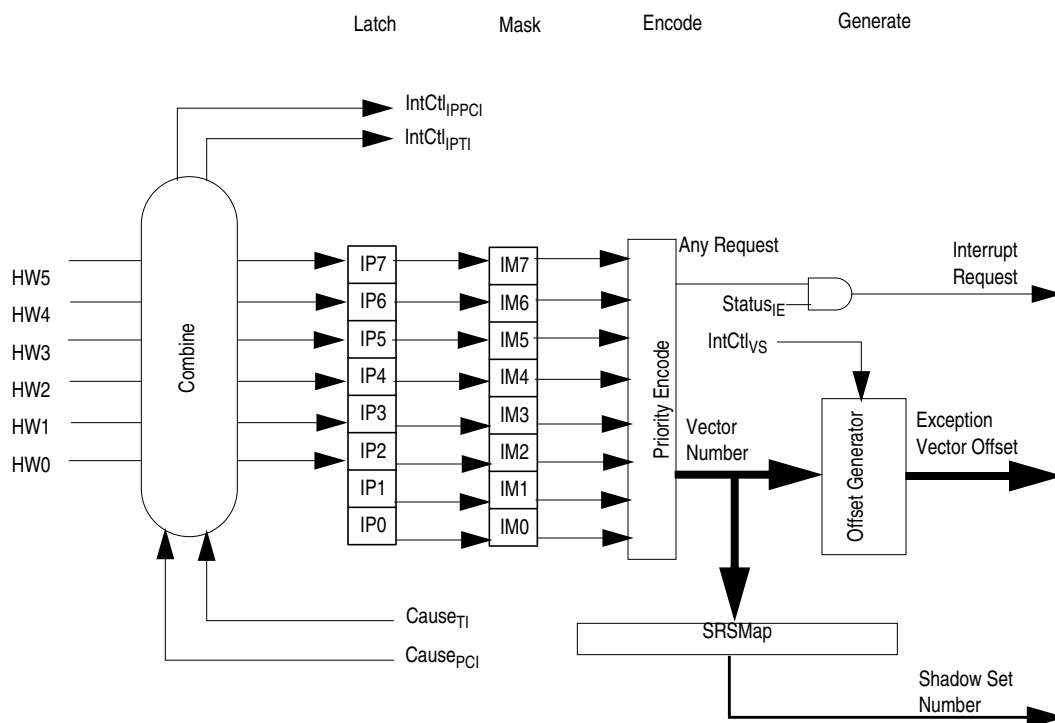
- $Config3_{VInt} = 1$
- $Config3_{VEIC} = 0$
- $IntCtl_{VS} \neq 0$
- $Cause_{IV} = 1$
- $Status_{BEV} = 0$

In VI interrupt mode, the six hardware interrupts are interpreted as individual hardware interrupt requests. The timer and performance counter interrupts are combined in a system-dependent way (external to the core) with the hardware interrupts (the interrupt with which they are combined is indicated by the *IntCtl_{IPTI/IPCI}* fields) to provide the appropriate relative priority of those interrupts with that of the hardware interrupts. The processor interrupt logic ANDs each of the *CauseIP* bits with the corresponding *Status_{IM}* bits. If any of these values is 1, and if interrupts are enabled (*Status_{IE}* = 1, *Status_{EXL}* = 0, and *Status_{ERL}* = 0), an interrupt is signaled and a priority encoder scans the values in the order shown in [Table 5.3](#).

Table 5.3 Relative Interrupt Priority for Vectored Interrupt Mode

| Relative Priority | Interrupt Type | Interrupt Source | Interrupt Request Calculated From | Vector Number Generated by Priority Encoder |
|-------------------|----------------|------------------|-----------------------------------|---|
| Highest Priority | Hardware | HW5 | IP7 and IM7 | 7 |
| | | HW4 | IP6 and IM6 | 6 |
| | | HW3 | IP5 and IM5 | 5 |
| | | HW2 | IP4 and IM4 | 4 |
| | | HW1 | IP3 and IM3 | 3 |
| | | HW0 | IP2 and IM2 | 2 |
| Lowest Priority | Software | SW1 | IP1 and IM1 | 1 |
| | | SW0 | IP0 and IM0 | 0 |

The priority order places a relative priority on each hardware interrupt and places the software interrupts at a priority lower than all hardware interrupts. When the priority encoder finds the highest priority pending interrupt, it outputs an encoded vector number that is used in the calculation of the handler for that interrupt, as described below. This is shown pictorially in [Figure 5.1](#).

Figure 5.1 Interrupt Generation for Vectored Interrupt Mode

A typical software handler for vectored interrupt mode bypasses the entire sequence of code following the IVexception label shown for the compatibility mode handler above. Instead, the hardware performs the prioritization, dispatching directly to the interrupt processing routine. Unlike the compatibility mode examples, a vectored interrupt handler may take advantage of a dedicated GPR shadow set to avoid saving any registers. As such, the SimpleInterrupt code shown above need not save the GPRs.

A nested interrupt is similar to that shown for compatibility mode, but may also take advantage of running the nested exception routine in the GPR shadow set dedicated to the interrupt or in another shadow set. Such a routine might look as follows:

```
NestedException:
/*
 * Nested exceptions typically require saving the EPC, Status and SRSTctl registers,
 * setting up the appropriate GPR shadow set for the routine, disabling
 * the appropriate IM bits in Status to prevent an interrupt loop, putting
 * the processor in kernel mode, and re-enabling interrupts. The sample code
 * below can not cover all nuances of this processing and is intended only
 * to demonstrate the concepts.
 */

/* Use the current GPR shadow set, and setup software context */
mfc0 k0, C0_EPC          /* Get restart address */
sw   k0, EPCTSave        /* Save in memory */
mfc0 k0, C0_Status       /* Get Status value */
sw   k0, StatusSave      /* Save in memory */
mfc0 k0, C0_SRSTctl      /* Save SRSTctl if changing shadow sets */
sw   k0, SRSTctlSave
li   k1, ~IMbitsToClear /* Get Im bits to clear for this interrupt */
/* this must include at least the IM bit */
```

```

/* for the current interrupt, and may include */
/* others */
and    k0, k0, k1          /* Clear bits in copy of Status */
/* If switching shadow sets, write new value to SRSCtl_PSS here */
ins    k0, zero, S_StatusEXL, (W_StatusKSU+W_StatusERL+W_StatusEXL)
/* Clear KSU, ERL, EXL bits in k0 */
mtc0   k0, C0_Status       /* Modify mask, switch to kernel mode, */
/* re-enable interrupts */

/*
 * If switching shadow sets, clear only KSU above, write target
 * address to EPC, and do execute an eret to clear EXL, switch
 * shadow sets, and jump to routine
 */

/* Process interrupt here, including clearing device interrupt */

/*
 * To complete interrupt processing, the saved values must be restored
 * and the original interrupted code restarted.
 */

di      /* Disable interrupts - may not be required */
lw      k0, StatusSave     /* Get saved Status (including EXL set) */
lw      k1, EPCHandle      /* and EPC */
mtc0    k0, C0_Status       /* Restore the original value */
lw      k0, SRSCtlSave     /* Get saved SRSCtl */
mtc0    k1, C0_EPC         /* and EPC */
mtc0    k0, C0_SRSCtl      /* Restore shadow sets */
ehb     /* Clear hazard */
eret    /* Dismiss the interrupt */

```

5.3.1.3 External Interrupt Controller Mode

External Interrupt Controller Mode redefines the way that the processor interrupt logic is configured to provide support for an external interrupt controller. The interrupt controller is responsible for prioritizing all interrupts, including hardware, software, timer, and performance counter interrupts, and directly supplying to the processor the vector number of the highest priority interrupt. EIC interrupt mode is in effect if all of the following conditions are true:

- $Config3_{VEIC} = 1$
- $IntCtl_{VS} \neq 0$
- $Cause_{IV} = 1$
- $Status_{BEV} = 0$

In EIC interrupt mode, the processor sends the state of the software interrupt requests ($Cause_{IP1..IP0}$) and the timer and performance counter interrupt requests ($Cause_{TI/PCI}$) to the external interrupt controller, where it prioritizes these interrupts in a system-dependent way with other hardware interrupts. The interrupt controller can be a hard-wired logic block, or it can be configurable based on control and status registers. This allows the interrupt controller to be more specific or more general as a function of the system environment and needs.

The external interrupt controller prioritizes its interrupt requests and produces the vector number of the highest priority interrupt to be serviced. The vector number, called the Requested Interrupt Priority Level (RIPL), is a 6-bit encoded value in the range 0..63, inclusive. A value of 0 indicates that no interrupt requests are pending. The values

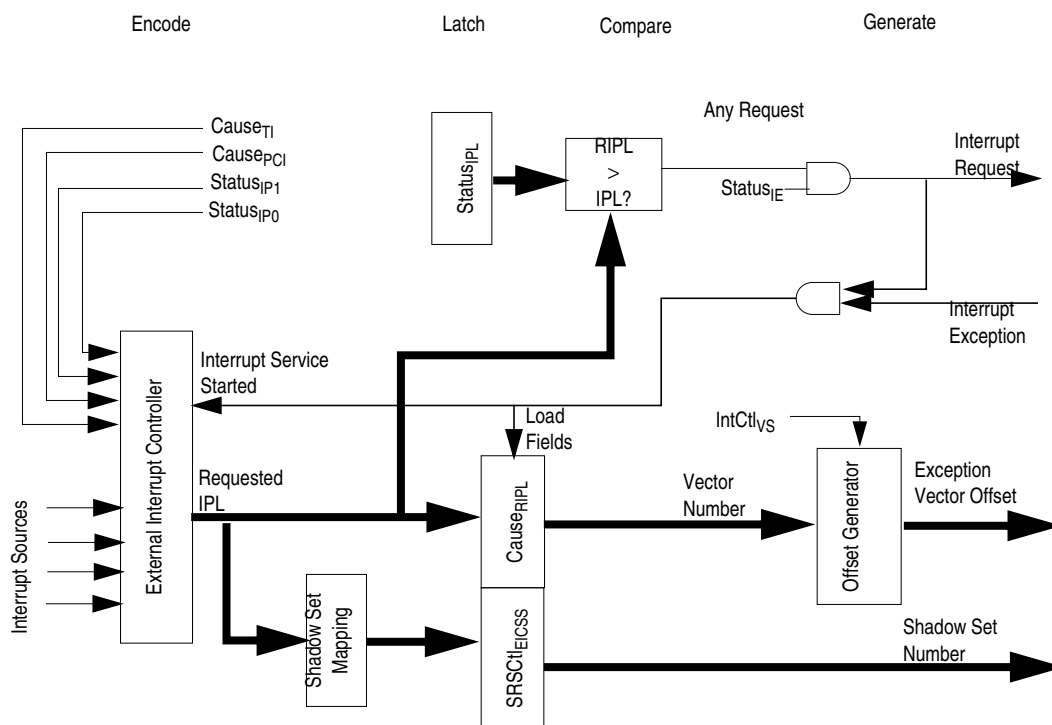
1..63 represent the lowest (1) to highest (63) RIPL for the interrupt to be serviced. The interrupt controller passes this value on the 6 hardware interrupt line, which are treated as an encoded value in EIC interrupt mode.

$Status_{IPL}$ (which overlays $Status_{IM7..IM2}$) is interpreted as the Interrupt Priority Level (IPL) at which the processor is currently operating (with a value of zero indicating that no interrupt is currently being serviced). When the interrupt controller requests service for an interrupt, the processor compares RIPL with $Status_{IPL}$ to determine if the requested interrupt has higher priority than the current IPL. If RIPL is strictly greater than $Status_{IPL}$, and interrupts are enabled ($Status_{IE} = 1$, $Status_{EXL} = 0$, and $Status_{ERL} = 0$) an interrupt request is signaled to the pipeline. When the processor starts the interrupt exception, it loads RIPL into $Cause_{RIPL}$ (which overlays $Cause_{IP7..IP2}$) and signals the external interrupt controller to notify it that the request is being serviced. The interrupt exception uses the value of $Cause_{RIPL}$ as the vector number. Because $Cause_{RIPL}$ is only loaded by the processor when an interrupt exception is signaled, it is available to software during interrupt processing.

In EIC interrupt mode, the external interrupt controller is also responsible for supplying the GPR shadow set number to use when servicing the interrupt. As such, the *SRSMap* register is not used in this mode, and the mapping of the vectored interrupt to a GPR shadow set is done by programming (or designing) the interrupt controller to provide the correct GPR shadow set number when an interrupt is requested. When the processor loads an interrupt request into $Cause_{RIPL}$, it also loads the GPR shadow set number into $SRSCtl_{EICSS}$, which is copied to $SRSCtl_{CSS}$ when the interrupt is serviced.

The operation of EIC interrupt mode is shown pictorially in Figure 5.2.

Figure 5.2 Interrupt Generation for External Interrupt Controller Interrupt Mode



A typical software handler for EIC interrupt mode bypasses the entire sequence of code following the IVexception label shown for the compatibility mode handler above. Instead, the hardware performs the prioritization, dispatching directly to the interrupt processing routine. Unlike the compatibility mode examples, an EIC interrupt handler may

take advantage of a dedicated GPR shadow set to avoid saving any registers. As such, the SimpleInterrupt code shown above need not save the GPRs.

A nested interrupt is similar to that shown for compatibility mode, but may also take advantage of running the nested exception routine in the GPR shadow set dedicated to the interrupt or in another shadow set. It also need only copy *Cause_{RIPL}* to *Status_{IPL}* to prevent lower priority interrupts from interrupting the handler. Such a routine might look as follows:

```
NestedException:
/*
 * Nested exceptions typically require saving the EPC, Status, and SRSCtl registers,
 * setting up the appropriate GPR shadow set for the routine, disabling
 * the appropriate IM bits in Status to prevent an interrupt loop, putting
 * the processor in kernel mode, and re-enabling interrupts. The sample code
 * below can not cover all nuances of this processing and is intended only
 * to demonstrate the concepts.
 */

/* Use the current GPR shadow set, and setup software context */
mfc0   k1, C0_Cause      /* Read Cause to get RIPL value */
mfc0   k0, C0_EPC        /* Get restart address */
srl    k1, k1, S_CauseRIPL /* Right justify RIPL field */
sw     k0, EPCSave       /* Save in memory */
mfc0   k0, C0_Status     /* Get Status value */
sw     k0, StatusSave    /* Save in memory */
ins    k0, k1, S_StatusIPL, 6 /* Set IPL to RIPL in copy of Status */
mfc0   k1, C0_SRSCtl     /* Save SRSCtl if changing shadow sets */
sw     k1, SRSCtlSave
/* If switching shadow sets, write new value to SRSCtl_PSS here */
ins    k0, zero, S_StatusEXL, (W_StatusKSU+W_StatusERL+W_StatusEXL)
/* Clear KSU, ERL, EXL bits in k0 */
mtc0   k0, C0_Status     /* Modify IPL, switch to kernel mode, */
/* re-enable interrupts */

/*
 * If switching shadow sets, clear only KSU above, write target
 * address to EPC, and do execute an eret to clear EXL, switch
 * shadow sets, and jump to routine
 */

/* Process interrupt here, including clearing device interrupt */

/*
 * The interrupt completion code is identical to that shown for VI mode above.
 */
```

5.3.2 Generation of Exception Vector Offsets for Vectored Interrupts

For vectored interrupts (in either VI or EIC interrupt mode), a vector number is produced by the interrupt control logic. This number is combined with *IntCtl_{VS}* to create the interrupt offset, which is added to 16#200 to create the exception vector offset. For VI interrupt mode, the vector number is in the range 0..7, inclusive. For EIC interrupt mode, the vector number is in the range 1..63, inclusive (0 being the encoding for “no interrupt”). The *IntCtl_{VS}* field specifies the spacing between vector locations. If this value is zero (the default reset state), the vector spacing is zero

and the processor reverts to Interrupt Compatibility Mode. A non-zero value enables vectored interrupts, and Table 5.4 shows the exception vector offset for a representative subset of the vector numbers and values of the *IntCtl_{VS}* field.

Table 5.4 Exception Vector Offsets for Vectored Interrupts

| Vector Number | Value of IntCtl _{VS} Field | | | | |
|---------------|-------------------------------------|---------|---------|---------|---------|
| | 2#00001 | 2#00010 | 2#00100 | 2#01000 | 2#10000 |
| 0 | 16#0200 | 16#0200 | 16#0200 | 16#0200 | 16#0200 |
| 1 | 16#0220 | 16#0240 | 16#0280 | 16#0300 | 16#0400 |
| 2 | 16#0240 | 16#0280 | 16#0300 | 16#0400 | 16#0600 |
| 3 | 16#0260 | 16#02C0 | 16#0380 | 16#0500 | 16#0800 |
| 4 | 16#0280 | 16#0300 | 16#0400 | 16#0600 | 16#0A00 |
| 5 | 16#02A0 | 16#0340 | 16#0480 | 16#0700 | 16#0C00 |
| 6 | 16#02C0 | 16#0380 | 16#0500 | 16#0800 | 16#0E00 |
| 7 | 16#02E0 | 16#03C0 | 16#0580 | 16#0900 | 16#1000 |
| | | • | | | |
| | | • | | | |
| | | • | | | |
| 61 | 16#09A0 | 16#1140 | 16#2080 | 16#3F00 | 16#7C00 |
| 62 | 16#09C0 | 16#1180 | 16#2100 | 16#4000 | 16#7E00 |
| 63 | 16#09E0 | 16#11C0 | 16#2180 | 16#4100 | 16#8000 |

The general equation for the exception vector offset for a vectored interrupt is:

$$\text{vectorOffset} \leftarrow 16\#200 + (\text{vectorNumber} \times (\text{IntCtl}_{\text{VS}} \parallel 2\#00000))$$

5.4 GPR Shadow Registers

Release 2 of the Architecture optionally removes the need to save and restore GPRs on entry to high priority interrupts or exceptions, and to provide specified processor modes with the same capability. This is done by introducing multiple copies of the GPRs, called *shadow sets*, and allowing privileged software to associate a shadow set with entry to kernel mode via an interrupt vector or exception. The normal GPRs are logically considered shadow set zero.

The number of GPR shadow sets is a build-time option on the 24K core. Although Release 2 of the Architecture defines a maximum of 16 shadow sets, the core allows one (the normal GPRs), two, or four shadow sets. The highest number actually implemented is indicated by the *SRSCtl_{HSS}* field. If this field is zero, only the normal GPRs are implemented.

Shadow sets are new copies of the GPRs that can be substituted for the normal GPRs on entry to kernel mode via an interrupt or exception. Once a shadow set is bound to a kernel mode entry condition, reference to GPRs work exactly as one would expect, but they are redirected to registers that are dedicated to that condition. Privileged software may need to reference all GPRs in the register file, even specific shadow registers that are not visible in the current mode. The RDPGPR and WRPGPR instructions are used for this purpose. The CSS field of the *SRSCtl* register provides the number of the current shadow register set, and the PSS field of the *SRSCtl* register provides the number of the previous shadow register set (that which was current before the last exception or interrupt occurred).

If the processor is operating in VI interrupt mode, binding of a vectored interrupt to a shadow set is done by writing to the *SRSMap* register. If the processor is operating in EIC interrupt mode, the binding of the interrupt to a specific

shadow set is provided by the external interrupt controller, and is configured in an implementation-dependent way. Binding of an exception or non-vectored interrupt to a shadow set is done by writing to the ESS field of the *SRSCtl* register. When an exception or interrupt occurs, the value of *SRSCtl*_{CSS} is copied to *SRSCtl*_{PSS}, and *SRSCtl*_{CSS} is set to the value taken from the appropriate source. On an ERET, the value of *SRSCtl*_{PSS} is copied back into *SRSCtl*_{CSS} to restore the shadow set of the mode to which control returns. More precisely, the rules for updating the fields in the *SRSCtl* register on an interrupt or exception are as follows:

1. No field in the *SRSCtl* register is updated if any of the following conditions is true. In this case, steps 2 and 3 are skipped.
 - The exception is one that sets *Status*_{ERL}: Reset or NMI.
 - The exception causes entry into EJTAG Debug Mode
 - *Status*_{BEV} = 1
 - *Status*_{EXL} = 1
2. *SRSCtl*_{CSS} is copied to *SRSCtl*_{PSS}
3. *SRSCtl*_{CSS} is updated from one of the following sources:
 - The appropriate field of the *SRSMap* register, based on IPL, if the exception is an interrupt, *Cause*_{IV} = 1, *Config3*_{VEIC} = 0, and *Config3*_{VInt} = 1. These are the conditions for a vectored interrupt.
 - The EICSS field of the *SRSCtl* register if the exception is an interrupt, *Cause*_{IV} = 1, and *Config3*_{VEIC} = 1. These are the conditions for a vectored EIC interrupt.
 - The ESS field of the *SRSCtl* register in any other case. This is the condition for a non-interrupt exception, or a non-vectored interrupt.

Similarly, the rules for updating the fields in the *SRSCtl* register at the end of an exception or interrupt are as follows:

1. No field in the *SRSCtl* register is updated if any of the following conditions is true. In this case, step 2 is skipped.
 - A DERET is executed
 - An ERET is executed with *Status*_{ERL} = 1
2. *SRSCtl*_{PSS} is copied to *SRSCtl*_{CSS}

These rules have the effect of preserving the *SRSCtl* register in any case of a nested exception or one which occurs before the processor has been fully initialized (*Status*_{BEV} = 1).

Privileged software may switch the current shadow set by writing a new value into *SRSCtl*_{PSS}, loading EPC with a target address, and doing an ERET.

5.5 Exception Vector Locations

The Reset, Soft Reset, NMI and EJTAG Debug exceptions are vectored to a specific location as shown in [Table 5.5](#) and [Table 5.6](#). Addresses for all other exceptions are a combination of a vector offset and a vector base address. In Release 1 of the architecture, the vector base address was fixed. In Release 2 of the architecture, software is allowed to specify the vector base address via the *EBase* register for exceptions that occur when *StatusBEV* equals 0. Another degree of flexibility in the selection of the vector base address, for use when *StatusBEV* equals 1, is provided via a set of input pins, *SI_UseExceptionBase* and *SI_ExceptionBase[29:12]*. [Table 5.5](#) gives the vector base address when *SI_UseExceptionBase* equals 0, as a function of the exception and whether the *BEV* bit is set in the *Status* register. [Table 5.6](#) gives the vector base addresses when *SI_UseExceptionBase* equals 1. As can be seen in [Table 5.6](#), when *SI_UseExceptionBase* equals 1, the exception vectors for cases where *StatusBEV* equals 0 are not affected.

[Table 5.7](#) gives the offsets from the vector base address as a function of the exception. Note that the IV bit in the *Cause* register causes Interrupts to use a dedicated exception vector offset, rather than the general exception vector. [Table 5.4](#) gives the offset from the base address in the case where *StatusBEV* = 0 and *CauseIV* = 1. [Table 5.8](#) combines these two tables into one that contains all possible vector addresses as a function of the state that can affect the vector selection. To avoid complexity in the table, it is assumed that *IntCtlVS* is 0.

Table 5.5 Exception Vector Base Addresses when *SI_UseExceptionBase* equals 0

| Exception | Status _{BEV} | |
|---|---|--------------|
| | 0 | 1 |
| Reset, NMI | 16#BFC0.0000 | |
| EJTAG Debug (with ProbEn = 0 in the EJTAG_Control_register) | 16#BFC0.0480 | |
| EJTAG Debug (with ProbEn = 1 in the EJTAG_Control_register) | 16#FF20.0200 | |
| Cache Error | EBase _{31..30} 1 EBase _{28..12} 16#000 Note that EBase _{31..30} have the fixed value 2#10 | 16#BFC0.0300 |
| Other | EBase _{31..12} 16#000 Note that EBase _{31..30} have the fixed value 2#10 | 16#BFC0.0200 |
| ‘ ’ denotes bit string concatenation | | |

Table 5.6 Exception Vector Base Addresses when *SI_UseExceptionBase* equals 1

| Exception | Status _{BEV} | |
|---|---|---|
| | 0 | 1 |
| Reset, NMI | 2#10 SI_ExceptionBase[29:12] 16#000 | |
| EJTAG Debug (with ProbEn = 0 in the EJTAG_Control_register) | 2#10 SI_ExceptionBase[29:12] 16#480 | |

| Exception | Status _{BEV} | |
|---|---|--|
| | 0 | 1 |
| EJTAG Debug (with ProbEn = 1 in the EJTAG_Control_register) | 16#FF20.0200 | |
| Cache Error | EBase _{31..30} 1 EBase _{28..12} 16#000 Note that EBase _{31..30} have the fixed value 2#10 | 2#101 SI_ExceptionBase[28:12] 16#300 |
| Other | EBase _{31..12} 16#000 Note that EBase _{31..30} have the fixed value 2#10 | 2#10 SI_ExceptionBase[29:12] 16#200 |
| ‘ ’ denotes bit string concatenation | | |

Table 5.7 Exception Vector Offsets

| Exception | Vector Offset |
|------------------------------------|--|
| TLB Refill, EXL = 0 | 16#000 |
| General Exception | 16#180 |
| Interrupt, Cause _{IV} = 1 | 16#200 (this is the base of the vectored interrupt table when Status _{BEV} = 0) |
| Reset, NMI | None (Uses Reset Base Address) |

Table 5.8 Exception Vectors

| Exception | SI_UseExceptionBase | Status _{BEV} | Status _{EXL} | Cause _{IV} | EJTAG ProbEn | Vector Assumes that IntCtl _{VS} = 0 |
|-------------|---------------------|-----------------------|-----------------------|---------------------|--------------|---|
| Reset, NMI | 0 | x | x | x | x | 16#BFC0.0000 |
| Reset, NMI | 1 | x | x | x | x | 2#10 SI_ExceptionBase[29:12] 16#000 |
| EJTAG Debug | 0 | x | x | x | 0 | 16#BFC0.0480 |
| EJTAG Debug | 1 | x | x | x | 0 | 2#10 SI_ExceptionBase[29:12] 16#480 |
| EJTAG Debug | x | x | x | x | 1 | 16#FF20.0200 |
| TLB Refill | 0 | 0 | 1 | x | x | 16#EBase[31:12] 16#180 |
| TLB Refill | 0 | 1 | 0 | x | x | 16#BFC0.0200 |
| TLB Refill | 1 | 1 | 0 | x | x | 2#10 SI_ExceptionBase[29:12] 16#200 |
| TLB Refill | 0 | 1 | 1 | x | x | 16#BFC0.0380 |

Table 5.8 Exception Vectors (Continued)

| Exception | SI_ExceptionBase | StatusBEV | StatusEXL | CauseV | EJTAG Proben | Vector Assumes that IntCtl _{VS} = 0 |
|---|------------------|-----------|-----------|--------|--------------|--|
| TLB Refill | 1 | 1 | 1 | x | x | 2#10 SI_ExceptionBase[29:12] 16#380 |
| Cache Error | 0 | 0 | x | x | x | 16#EBase[31:30] 2#1 EBase[28:12] 16#100 |
| Cache Error | 0 | 1 | x | x | x | 16#BFC0.0300 |
| Cache Error | 1 | 1 | x | x | x | 2#101 SI_ExceptionBase[28:12] 16#300 |
| Interrupt | x | 0 | 0 | 0 | x | 16#EBase[31:12] 16#180 |
| Interrupt | x | 0 | 0 | 1 | x | 16#EBase[31:12] 16#200 |
| Interrupt | 0 | 1 | 0 | 0 | x | 16#BFC0.0380 |
| Interrupt | 1 | 1 | 0 | 0 | x | 2#10 SI_ExceptionBase[29:12] 16#380 |
| Interrupt | 0 | 1 | 0 | 1 | x | 16#BFC0.0400 |
| Interrupt | 1 | 1 | 0 | 1 | x | 2#10 SI_ExceptionBase[29:12] 16#400 |
| All others | 0 | 0 | x | x | x | 16#EBase[31:12] 16#180 |
| All others | 0 | 1 | x | x | x | 16#BFC0.0380 |
| All others | 1 | 1 | x | x | x | 2#10 SI_ExceptionBase[29:12] 16#380 |
| 'x' denotes don't care, ' ' denotes bit string concatenation | | | | | | |

5.6 General Exception Processing

With the exception of Reset, NMI, cache error, and EJTAG Debug exceptions, which have their own special processing as described below, exceptions have the same basic processing flow:

- If the *EXL* bit in the *Status* register is zero, the *EPC* register is loaded with the PC at which execution will be restarted and the *BD* bit is set appropriately in the *Cause* register (see Table 6.24). The value loaded into the *EPC* register is dependent on whether the processor implements the MIPS16 ASE, and whether the instruction is in the delay slot of a branch or jump which has delay slots. Table 5.9 shows the value stored in each of the CP0 PC registers, including *EPC*. For implementations of Release 2 of the Architecture if *Status_{BEV}* = 0, the *CSS* field in the *SRSCtl* register is copied to the *PSS* field, and the *CSS* value is loaded from the appropriate source.

If the *EXL* bit in the *Status* register is set, the *EPC* register is not loaded and the *BD* bit is not changed in the *Cause* register. For implementations of Release 2 of the Architecture, the *SRSCtl* register is not changed.

Table 5.9 Value Stored in EPC, ErrorEPC, or DEPC on an Exception

| MIPS16 Implemented? | In Branch/Jump Delay Slot? | Value stored in EPC/ErrorEPC/DEPC |
|---------------------|----------------------------|--|
| No | No | Address of the instruction |
| No | Yes | Address of the branch or jump instruction (PC-4) |

Table 5.9 Value Stored in EPC, ErrorEPC, or DEPC on an Exception

| MIPS16 Implemented? | In Branch/Jump Delay Slot? | Value stored in EPC/ErrorEPC/DEPC |
|---------------------|----------------------------|--|
| Yes | No | Upper 31 bits of the address of the instruction, combined with the <i>ISA Mode</i> bit |
| Yes | Yes | Upper 31 bits of the branch or jump instruction (PC-2 in the MIPS16 ISA Mode and PC-4 in the 32-bit ISA Mode), combined with the <i>ISA Mode</i> bit |

- The *CE*, and *ExcCode* fields of the *Cause* registers are loaded with the values appropriate to the exception. The *CE* field is loaded, but not defined, for any exception type other than a coprocessor unusable exception.
- The *EXL* bit is set in the *Status* register.
- The processor is started at the exception vector.

The value loaded into *EPC* represents the restart address for the exception and need not be modified by exception handler software in the normal case. Software need not look at the *BD* bit in the *Cause* register unless it wishes to identify the address of the instruction that actually caused the exception.

Note that individual exception types may load additional information into other registers. This is noted in the description of each exception type below.

Operation:

```

/* If StatusEXL is 1, all exceptions go through the general exception vector */
/* and neither EPC nor CauseBD nor SRStl are modified */
if StatusEXL = 1 then
    vectorOffset ← 16#180
else
    /* For implementations that include the MIPS16e ASE, calculate potential */
    /* PC adjustment for exceptions in the delay slot */
    if Config1CA = 0 then
        restartPC ← PC
        branchAdjust ← 4          /* Possible adjustment for delay slot */
    else
        restartPC ← PC31..1 || ISAMode
        if (ISAMode = 0) or ExtendedMIPS16Instruction
            branchAdjust ← 4      /* Possible adjustment for 32-bit MIPS delay slot */
        else
            branchAdjust ← 2      /* Possible adjustment for MIPS16 delay slot */
        endif
    endif
endif
if InstructionInBranchDelaySlot then
    EPC ← restartPC - branchAdjust /* PC of branch/jump */
    CauseBD ← 1
else
    EPC ← restartPC                /* PC of instruction */
    CauseBD ← 0
endif

/* Compute vector offsets as a function of the type of exception */
NewShadowSet ← SRStlESS          /* Assume exception, Release 2 only */
if ExceptionType = TLBRefill then
    vectorOffset ← 16#000

```

```

elseif (ExceptionType = Interrupt) then
  if (CauseIV = 0) then
    vectorOffset ← 16#180
  else
    if (StatusBEV = 1) or (IntCtlVS = 0) then
      vectorOffset ← 16#200
    else
      if Config3VEIC = 1 then
        VecNum ← CauseRIPL
        NewShadowSet ← SRSCtlEICSS
      else
        VecNum ← VIntPriorityEncoder()
        NewShadowSet ← SRSMaPIPL4+3..IPL4
      endif
      vectorOffset ← 16#200 + (VecNum × (IntCtlVS || 2#00000))
    endif /* if (StatusBEV = 1) or (IntCtlVS = 0) then */
  endif /* if (CauseIV = 0) then */
endif /* elseif (ExceptionType = Interrupt) then */

/* Update the shadow set information for an implementation of */
/* Release 2 of the architecture */
if ((ArchitectureRevision ≥ 2) and (SRSCtlHSS > 0) and (StatusBEV = 0) and
    (StatusERL = 0)) then
  SRSCtlPSS ← SRSCtlCSS
  SRSCtlCSS ← NewShadowSet
endif
endif /* if StatusEXL = 1 then */

CauseCE ← FaultingCoprocesorNumber
CauseExcCode ← ExceptionType
StatusEXL ← 1

if Config1CA = 1 then
  ISAMode ← 0
endif

/* Calculate the vector base address */
if StatusBEV = 1 then
  vectorBase ← 16#BFC0.0200
else
  if ArchitectureRevision ≥ 2 then
    /* The fixed value of EBase31..30 forces the base to be in kseg0 or kseg1 */
    vectorBase ← EBase31..12 || 16#000
  else
    vectorBase ← 16#8000.0000
  endif
endif

/* Exception PC is the sum of vectorBase and vectorOffset */
PC ← vectorBase31..30 || (vectorBase29..0 + vectorOffset29..0)
/* No carry between bits 29 and 30 */

```

5.7 Debug Exception Processing

All debug exceptions have the same basic processing flow:

- The *DEPC* register is loaded with the program counter (PC) value at which execution will be restarted and the DBD bit is set appropriately in the *Debug* register. The value loaded into the *DEPC* register is the current PC if the instruction is not in the delay slot of a branch, or the PC-4 of the branch if the instruction is in the delay slot of a branch.
- The DSS, DBp, DDBL, DDBS, DIB and DINT bits (D* bits at [5:0]) in the *Debug* register are updated appropriately depending on the debug exception type.
- Halt and Doze bits in the *Debug* register are updated appropriately.
- DM bit in the *Debug* register is set to 1.
- The processor is started at the debug exception vector.

The value loaded into *DEPC* represents the restart address for the debug exception and need not be modified by the debug exception handler software in the usual case. Debug software need not look at the DBD bit in the *Debug* register unless it wishes to identify the address of the instruction that actually caused the debug exception.

A unique debug exception is indicated through the DSS, DBp, DDBL, DDBS, DIB and DINT bits (D* bits at [5:0]) in the *Debug* register.

No other CP0 registers or fields are changed due to the debug exception, thus no additional state is saved.

Operation:

```

if InstructionInBranchDelaySlot then
    DEPC ← PC-4
    DebugDBD ← 1
else
    DEPC ← PC
    DebugDBD ← 0
endif
DebugD* bits at [5:0] ← DebugExceptionType
DebugHalt ← HaltStatusAtDebugException
DebugDoze ← DozeStatusAtDebugException
DebugDM ← 1
if EJTAGControlRegisterProbTrap = 1 then
    PC ← 0xFF20_0200
else
    PC ← 0xBFC0_0480
endif
    
```

The same debug exception vector location is used for all debug exceptions. The location is determined by the Prob-Trap bit in the EJTAG Control register (ECR), as shown in [Table 5.10](#).

Table 5.10 Debug Exception Vector Addresses

| ProbTrap bit in ECR Register | Debug Exception Vector Address |
|------------------------------|--------------------------------|
| 0 | 0xBFC0_0480 |
| 1 | 0xFF20_0200 in dmseg |

5.8 Exceptions

The following subsections describe each of the exceptions listed in the same sequence as shown in [Table 5.1](#).

5.8.1 Reset Exception

A reset exception occurs when the *SI_Reset* signal is asserted to the processor. This exception is not maskable. When a Reset exception occurs, the processor performs a full reset initialization, including aborting state machines, establishing critical state, and generally placing the processor in a state in which it can execute instructions from uncached, unmapped address space. On a Reset exception, the state of the processor is not defined, with the following exceptions:

- The *Random* register is initialized to the number of TLB entries - 1.
- The *Wired* register is initialized to zero.
- The *Config* register is initialized with its boot state.
- The RP, BEV, TS, SR, NMI, and ERL fields of the *Status* register are initialized to a specified state.
- The I, R, and W fields of the *WatchLo* register are initialized to 0.
- The *ErrorEPC* register is loaded with PC-4 if the state of the processor indicates that it was executing an instruction in the delay slot of a branch. Otherwise, the *ErrorEPC* register is loaded with PC. Note that this value may or may not be predictable.
- PC is loaded with 0xBFC0_0000.

Cause Register ExcCode Value:

None

Additional State Saved:

None

Entry Vector Used:

Reset (0xBFC0_0000)

Operation:

```

Random ← TLBEntries - 1
Wired ← 0
Config ← ConfigurationState
StatusRP ← 0
StatusBEV ← 1
StatusTS ← 0
StatusSR ← 0
StatusNMI ← 0
StatusERL ← 1
WatchLoI ← 0
WatchLoR ← 0
WatchLoW ← 0
if InstructionInBranchDelaySlot then
    ErrorEPC ← PC - 4

```

```

else
    ErrorEPC ← PC
endif
PC ← 0xBFC0_0000

```

5.8.2 Debug Single Step Exception

A debug single step exception occurs after the CPU has executed one/two instructions in non-debug mode, when returning to non-debug mode after debug mode. One instruction is allowed to execute when returning to an instruction without a delay slot, otherwise two instructions are allowed to execute since the jump/branch and the instruction in the delay slot are executed as one step. Debug single step exceptions are enabled by the SSt bit in the *Debug* register, and are always disabled for the first one/two instructions after a DERET.

The *DEPC* register points to the instruction on which the debug single step exception occurred, which is also the next instruction to single step or execute when returning from debug mode. So the *DEPC* will not point to the instruction which has just been single stepped, but rather the following instruction. The DBD bit in the *Debug* register is never set for a debug single step exception, since the jump/branch and the instruction in the delay slot is executed in one step.

Exceptions occurring on the instruction(s) executed with debug single step exception enabled are taken even though debug single step was enabled. For a normal exception (other than reset), a debug single step exception is then taken on the first instruction in the normal exception handler. Debug exceptions are unaffected by single step mode, e.g. returning to a SDBBP instruction with debug single step exceptions enabled causes a debug software breakpoint exception, and the *DEPC* will point to the SDBBP instruction. However, returning to an instruction (not jump/branch) just before the SDBBP instruction, causes a debug single step exception with the *DEPC* pointing to the SDBBP instruction.

To ensure proper functionality of single step, the debug single step exception has priority over all other exceptions, except reset and soft reset.

Debug Register Debug Status Bit Set

DSS

Additional State Saved

None

Entry Vector Used

Debug exception vector

5.8.3 Debug Interrupt Exception

A debug interrupt exception is either caused by the EjtagBrk bit in the *EJTAG Control* register (controlled through the TAP), or caused by the debug interrupt request signal to the CPU.

The debug interrupt exception is an asynchronous debug exception which is taken as soon as possible, but with no specific relation to the executed instructions. The *DEPC* register is set to the instruction where execution should continue after the debug handler is through. The DBD bit is set based on whether the interrupted instruction was executing in the delay slot of a branch.

Debug Register Debug Status Bit Set

DINT

Additional State Saved

None

Entry Vector Used

Debug exception vector

5.8.4 Non-Maskable Interrupt (NMI) Exception

A non maskable interrupt exception occurs when the *SI_NMI* signal is asserted to the processor. *SI_NMI* is an edge sensitive signal - only one NMI exception will be taken each time it is asserted. An NMI exception occurs only at instruction boundaries, so it does not cause any reset or other hardware initialization. The state of the cache, memory, and other processor states are consistent and all registers are preserved, with the following exceptions:

- The BEV, TS, SR, NMI, and ERL fields of the *Status* register are initialized to a specified state.
- The *ErrorEPC* register is loaded with PC-4 if the state of the processor indicates that it was executing an instruction in the delay slot of a branch. Otherwise, the *ErrorEPC* register is loaded with PC.
- PC is loaded with 0xBFC0_0000.

Cause Register ExcCode Value:

None

Additional State Saved:

None

Entry Vector Used:

Reset (0xBFC0_0000)

Operation:

```

Status_BEV ← 1
Status_TS ← 0
Status_SR ← 0
Status_NMI ← 1
Status_ERL ← 1
if InstructionInBranchDelaySlot then
    ErrorEPC ← PC - 4
else
    ErrorEPC ← PC
endif
PC ← 0xBFC0_0000

```

5.8.5 Machine Check Exception

A machine check exception occurs when the processor detects an internal inconsistency. The following condition causes a machine check exception:

- The detection of multiple matching entries in the TLB. The core detects this condition on a TLB write and prevents the write from being completed. The TS bit in the *Status* register is set to indicate this condition. This bit is only a status flag and does not affect the operation of the device. Software clears this bit at the appropriate time. This condition is resolved by flushing the conflicting TLB entries. The TLB write can then be completed.

Cause Register ExcCode Value:

MCheck

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.6 Interrupt Exception

The interrupt exception occurs when one or more of the six hardware, two software, or timer interrupt requests is enabled by the *Status* register and the interrupt input is asserted. See [Section 5.3 “Interrupts”](#) for more details about the processing of interrupts.

Register ExcCode Value:

Int

Additional State Saved:

Table 5.11 Register States an Interrupt Exception

| Register State | Value |
|----------------|--|
| <i>CauseIp</i> | indicates the interrupts that are pending. |

Entry Vector Used:

See [Section 5.3.2 “Generation of Exception Vector Offsets for Vectored Interrupts”](#) for the entry vector used, depending on the interrupt mode the processor is operating in.

5.8.7 Debug Instruction Break Exception

A debug instruction break exception occurs when an instruction hardware breakpoint matches an executed instruction. The *DEPC* register and DBD bit in the *Debug* register indicate the instruction that caused the instruction hardware breakpoint to match. This exception can only occur if instruction hardware breakpoints are implemented.

Debug Register Debug Status Bit Set:

DIB

Additional State Saved:

None

Entry Vector Used:

Debug exception vector

5.8.8 Watch Exception — Instruction Fetch or Data Access

The Watch facility provides a software debugging vehicle by initiating a watch exception when an instruction or data reference matches the address information stored in the *WatchHi* and *WatchLo* registers. A Watch exception is taken immediately if the *EXL* and *ERL* bits of the *Status* register are both zero and the *DM* bit of the *Debug* is also zero. If

any of those bits is a one at the time that a watch exception would normally be taken, then the *WP* bit in the *Cause* register is set, and the exception is deferred until all three bits are zero. Software may use the *WP* bit in the *Cause* register to determine if the *EPC* register points at the instruction that caused the watch exception, or if the exception actually occurred while in kernel mode.

The Watch exception can occur on either an instruction fetch or a data access. Watch exceptions that occur on an instruction fetch have a higher priority than watch exceptions that occur on a data access.

Register ExcCode Value:

WATCH

Additional State Saved:

Table 5.12 Register States on a Watch Exception

| Register State | Value |
|---------------------------------|---|
| <i>Cause</i> _{WP} | Indicates that the watch exception was deferred until after <i>Status</i> _{EXL} , <i>Status</i> _{ERL} , and <i>Debug</i> _{DM} were zero. This bit directly causes a watch exception, so software must clear this bit as part of the exception handler to prevent a watch exception loop at the end of the current handler execution. |
| <i>WatchHi</i> _{I,R,W} | Set for the watch channel that matched, and indicates which type of match there was. |

Entry Vector Used:

General exception vector (offset 0x180)

5.8.9 Address Error Exception — Instruction Fetch/Data Access

An address error exception occurs on an instruction or data access when an attempt is made to execute one of the following:

- Fetch an instruction, load a word, or store a word that is not aligned on a word boundary
- Load or store a halfword that is not aligned on a halfword boundary
- Reference the kernel address space from user mode

Note that in the case of an instruction fetch that is not aligned on a word boundary, PC is updated before the condition is detected. Therefore, both *EPC* and *BadVAddr* point to the unaligned instruction address. In the case of a data access the exception is taken if either an unaligned address or an address that was inaccessible in the current processor mode was referenced by a load or store instruction.

Cause Register ExcCode Value:

ADEL: Reference was a load or an instruction fetch

ADES: Reference was a store

Additional State Saved:**Table 5.13 CP0 Register States on an Address Exception Error**

| Register State | Value |
|--------------------------------|-----------------|
| <i>BadVAddr</i> | failing address |
| <i>Context</i> _{VPN2} | UNPREDICTABLE |
| <i>EntryHi</i> _{VPN2} | UNPREDICTABLE |
| <i>EntryLo0</i> | UNPREDICTABLE |
| <i>EntryLo1</i> | UNPREDICTABLE |

Entry Vector Used:

General exception vector (offset 0x180)

5.8.10 TLB Refill Exception — Instruction Fetch or Data Access

During an instruction fetch or data access, a TLB refill exception occurs when no TLB entry matches a reference to a mapped address space and the *EXL* bit is 0 in the *Status* register. Note that this is distinct from the case in which an entry matches but has the valid bit off. In that case, a TLB Invalid exception occurs.

Cause Register ExcCode Value:

TLBL: Reference was a load or an instruction fetch

TLBS: Reference was a store

Additional State Saved:**Table 5.14 CP0 Register States on a TLB Refill Exception**

| Register State | Value |
|-----------------|--|
| <i>BadVAddr</i> | failing address. |
| <i>Context</i> | The BadVPN2 field contains VA _{31:13} of the failing address. |
| <i>EntryHi</i> | The VPN2 field contains VA _{31:13} of the failing address; the ASID field contains the ASID of the reference that missed. |
| <i>EntryLo0</i> | UNPREDICTABLE |
| <i>EntryLo1</i> | UNPREDICTABLE |

Entry Vector Used:TLB refill vector (offset 0x000) if *Status*_{EXL} = 0 at the time of exception;general exception vector (offset 0x180) if *Status*_{EXL} = 1 at the time of exception**5.8.11 TLB Invalid Exception — Instruction Fetch or Data Access**

During an instruction fetch or data access, a TLB invalid exception occurs in one of the following cases:

- No TLB entry matches a reference to a mapped address space; and the *EXL* bit is 1 in the *Status* register.

- A TLB entry matches a reference to a mapped address space, but the matched entry has the valid bit off.

Cause Register ExcCode Value:

TLBL: Reference was a load or an instruction fetch

TLBS: Reference was a store

Additional State Saved:

Table 5.15 CP0 Register States on a TLB Invalid Exception

| Register State | Value |
|-----------------|--|
| <i>BadVAddr</i> | failing address |
| <i>Context</i> | The BadVPN2 field contains VA _{31:13} of the failing address. |
| <i>EntryHi</i> | The VPN2 field contains VA _{31:13} of the failing address; the ASID field contains the ASID of the reference that missed. |
| <i>EntryLo0</i> | UNPREDICTABLE |
| <i>EntryLo1</i> | UNPREDICTABLE |

Entry Vector Used:

General exception vector (offset 0x180)

5.8.12 Cache Error Exception

A cache error exception occurs when an instruction or data reference detects a cache tag or data error. This exception is not maskable. To avoid disturbing the error in the cache array the exception vector is to an unmapped, uncached address. This exception can be imprecise and the ErrorEPC may not point to the instruction that saw the error. L2 cache errors are considered to be imprecise. An L2 cache error on a data load operation can potentially corrupt the target GPR.

Cause Register ExcCode Value

N/A

Additional State Saved

Table 5.16 CP0 Register States on a Cache Error Exception

| Register State | Value |
|-----------------|-------------|
| <i>CacheErr</i> | Error state |
| <i>ErrorEPC</i> | Restart PC |

Entry Vector Used

Cache error vector (offset 16#100)

5.8.13 Bus Error Exception — Instruction Fetch or Data Access

A bus error exception occurs when an instruction or data access makes a bus request (due to a cache miss or an uncacheable reference) and that request terminates in an error. The bus error exception can occur on either an instruc-

tion fetch or a data read. Bus error exceptions cannot be generated on data writes. Bus error exceptions that occur on an instruction fetch have a higher priority than bus error exceptions that occur on a data access.

Bus Error exceptions on instruction fetch (IBE) are precise. Bus errors on data load operations (DBE) are considered to be imprecise. These errors are taken when the ERR code is returned on the *OC_SResp* input. Bus errors on data load operations can potentially corrupt the target GPR.

Cause Register ExcCode Value:

IBE: Error on an instruction reference

DBE: Error on a data reference

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.14 Debug Software Breakpoint Exception

A debug software breakpoint exception occurs when an SDBBP instruction is executed. The *DEPC* register and DBD bit in the *Debug* register will indicate the SDBBP instruction that caused the debug exception.

Debug Register Debug Status Bit Set:

DBp

Additional State Saved:

None

Entry Vector Used:

Debug exception vector

5.8.15 Execution Exception — System Call

The system call exception is one of the execution exceptions. All of these exceptions have the same priority. A system call exception occurs when a SYSCALL instruction is executed.

Cause Register ExcCode Value:

Sys

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.16 Execution Exception — Breakpoint

The breakpoint exception is one of the execution exceptions. All of these exceptions have the same priority. A breakpoint exception occurs when a BREAK instruction is executed.

Cause Register ExcCode Value:

Bp

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.17 Execution Exception — Reserved Instruction

The reserved instruction exception is one of the execution exceptions. All of these exceptions have the same priority. A reserved instruction exception occurs when a reserved or undefined major opcode or function field is executed. This includes Coprocessor 2 instructions which are decoded reserved in the Coprocessor 2.

Cause Register ExcCode Value:

RI

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.18 Execution Exception — Coprocessor Unusable

The coprocessor unusable exception is one of the execution exceptions. All of these exceptions have the same priority. A coprocessor unusable exception occurs when an attempt is made to execute a coprocessor instruction for one of the following:

- a corresponding coprocessor unit that has not been marked usable by setting its CU bit in the *Status* register
- CP0 instructions, when the unit has not been marked usable, and the processor is executing in user mode

Cause Register ExcCode Value:

CpU

Additional State Saved:

Table 5.17 Register States on a Coprocessor Unusable Exception

| Register State | Value |
|----------------------------|---|
| <i>Cause</i> _{CE} | unit number of the coprocessor being referenced |

Entry Vector Used:

General exception vector (offset 0x180)

5.8.19 Execution Exception — CorExtend block Unusable

The CorExtend block unusable exception is one of the execution exceptions. All of these exceptions have the same priority. A CEU exception occurs when an attempt is made to execute a CorExtend instruction when the CEE bit in the *Status* register is not set. It is dependent on the implementation of the CorExtend block, but this exception should be taken on any CorExtend instruction that modifies local state within the CorExtend block and can optionally be taken on other CorExtend instructions.

Cause Register ExcCode Value:

CEU

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.20 Execution Exception — Floating Point Exception

A floating point exception is initiated by the floating point coprocessor.

Cause Register ExcCode Value:

FPE

Additional State Saved:

Table 5.18 Register States on a Floating Point Exception

| Register State | Value |
|----------------|---|
| <i>FCSR</i> | Indicates the cause of the floating point exception |

Entry Vector Used:

General exception vector (offset 0x180)

5.8.21 Execution Exception — Integer Overflow

The integer overflow exception is one of the execution exceptions. All of these exceptions have the same priority. An integer overflow exception occurs when selected integer instructions result in a 2's complement overflow.

Cause Register ExcCode Value:

Ov

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.22 Execution Exception — Trap

The trap exception is one of the execution exceptions. All of these exceptions have the same priority. A trap exception occurs when a trap instruction results in a TRUE value.

Cause Register **ExcCode Value:**

Tr

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.23 Execution Exception — C2E

A C2E exception is signalled from the optional coprocessor2 block on a coprocessor instruction.

Cause Register **ExcCode Value:**

C2E

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.24 Execution Exception — IS1

An IS1 exception is signalled from the optional coprocessor2 block on a coprocessor instruction.

Cause Register **ExcCode Value:**

IS1

Additional State Saved:

None

Entry Vector Used:

General exception vector (offset 0x180)

5.8.25 Debug Data Break Exception

A debug data break exception occurs when a data hardware breakpoint matches the load/store transaction of an executed load/store instruction. The *DEPC* register and DBD bit in the *Debug* register will indicate the load/store instruction that caused the data hardware breakpoint to match. The load/store instruction that caused the debug exception has not completed e.g. not updated the register file, and the instruction can be re-executed after returning from the debug handler.

Debug Register Debug Status Bit Set:

DDBL for a load instruction or DDBS for a store instruction

Additional State Saved:

None

Entry Vector Used:

Debug exception vector

5.8.26 TLB Modified Exception — Data Access

During a data access, a TLB modified exception occurs on a store reference to a mapped address if the following condition is true:

- The matching TLB entry is valid, but not dirty.

Cause Register ExcCode Value:

Mod

Additional State Saved:

Table 5.19 Register States on a TLB Modified Exception

| Register State | Value |
|-----------------|--|
| <i>BadVAddr</i> | failing address |
| <i>Context</i> | The BadVPN2 field contains VA _{31:13} of the failing address. |
| <i>EntryHi</i> | The VPN2 field contains VA _{31:13} of the failing address; the ASID field contains the ASID of the reference that missed. |
| <i>EntryLo0</i> | UNPREDICTABLE |
| <i>EntryLo1</i> | UNPREDICTABLE |

Entry Vector Used:

General exception vector (offset 0x180)

5.9 Exception Handling and Servicing Flowcharts

The remainder of this chapter contains flowcharts for the following exceptions and guidelines for their handlers:

- General exceptions and their exception handler
- TLB miss exception and their exception handler
- Reset and NMI exceptions, and a guideline to their handler.
- Debug exceptions

Generally speaking, the exceptions are handled by hardware; the exceptions are then serviced by software. Note that unexpected debug exceptions to the debug exception vector at 0xBFC0_0200 may be viewed as a reserved instruction since uncontrolled execution of an SDBBP instruction caused the exception. The DERET instruction must be used at return from the debug exception handler, in order to leave debug mode and return to non-debug mode. The DERET instruction returns to the address in the *DEPC* register.

Figure 5.3 General Exception Handler (HW)

Exceptions other than Reset, NMI, or first-level TLB miss
Note: Interrupts can be masked by IE or
IMs and Watch is masked if EXL = 1

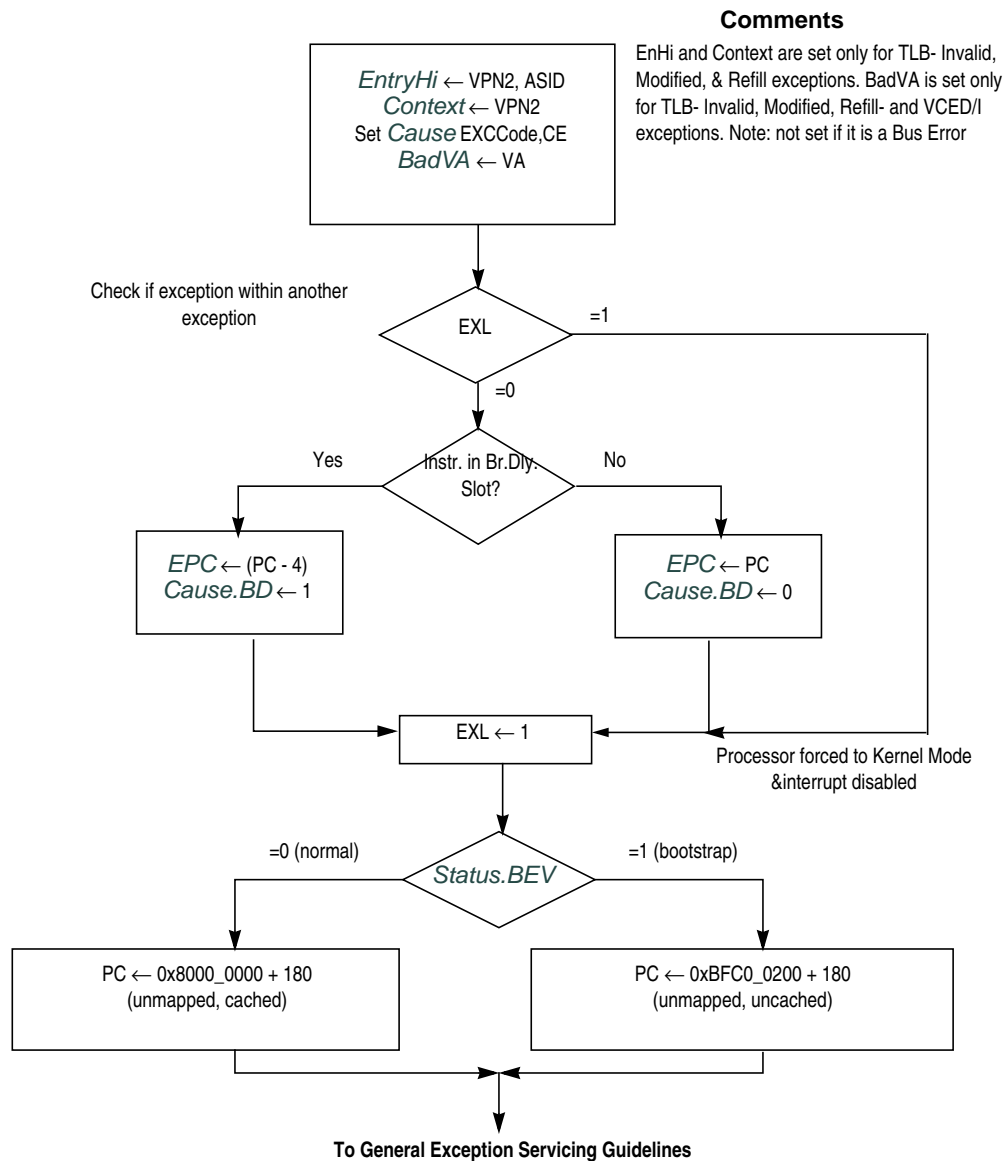


Figure 5.4 General Exception Servicing Guidelines (SW)

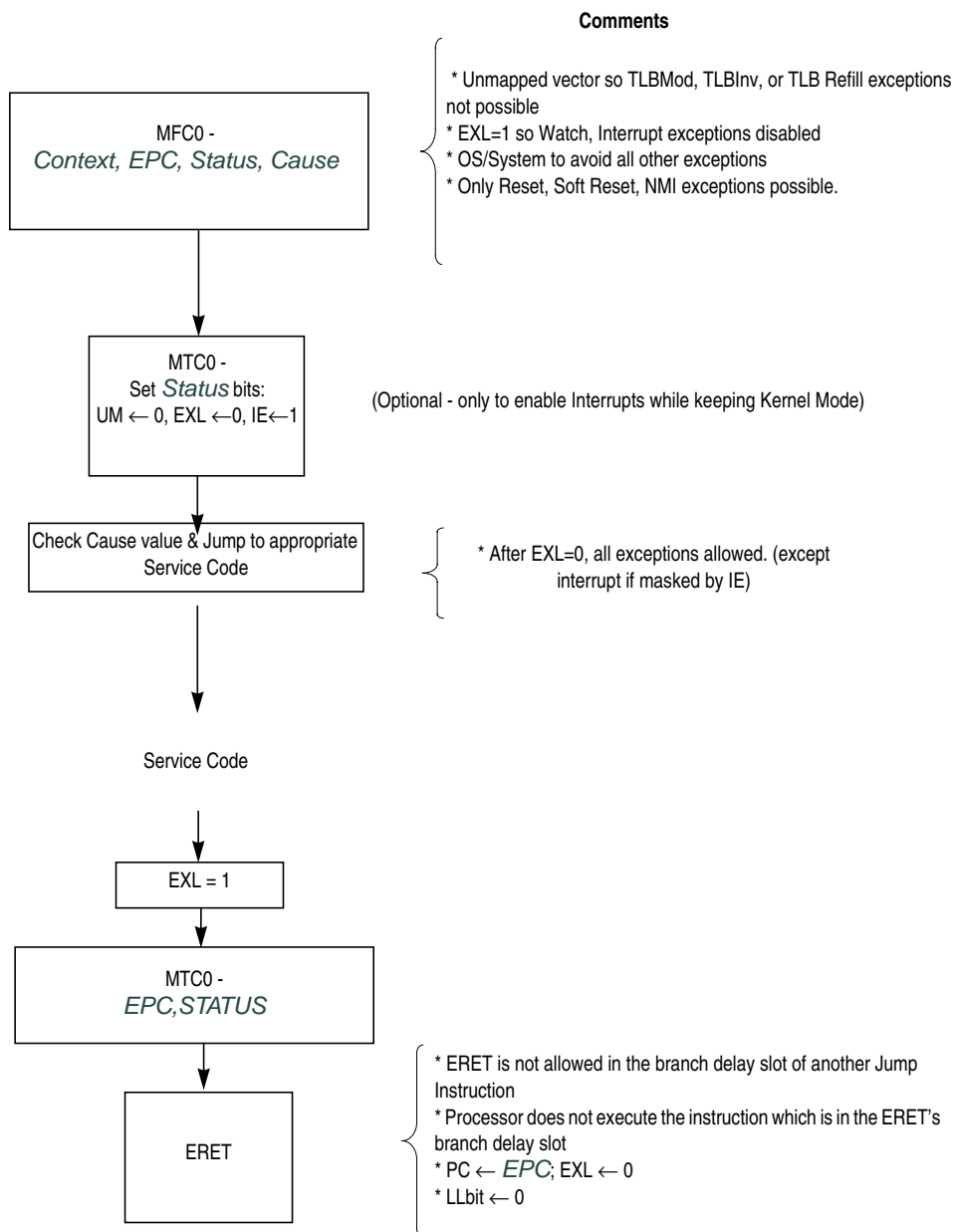


Figure 5.5 TLB Miss Exception Handler (HW)

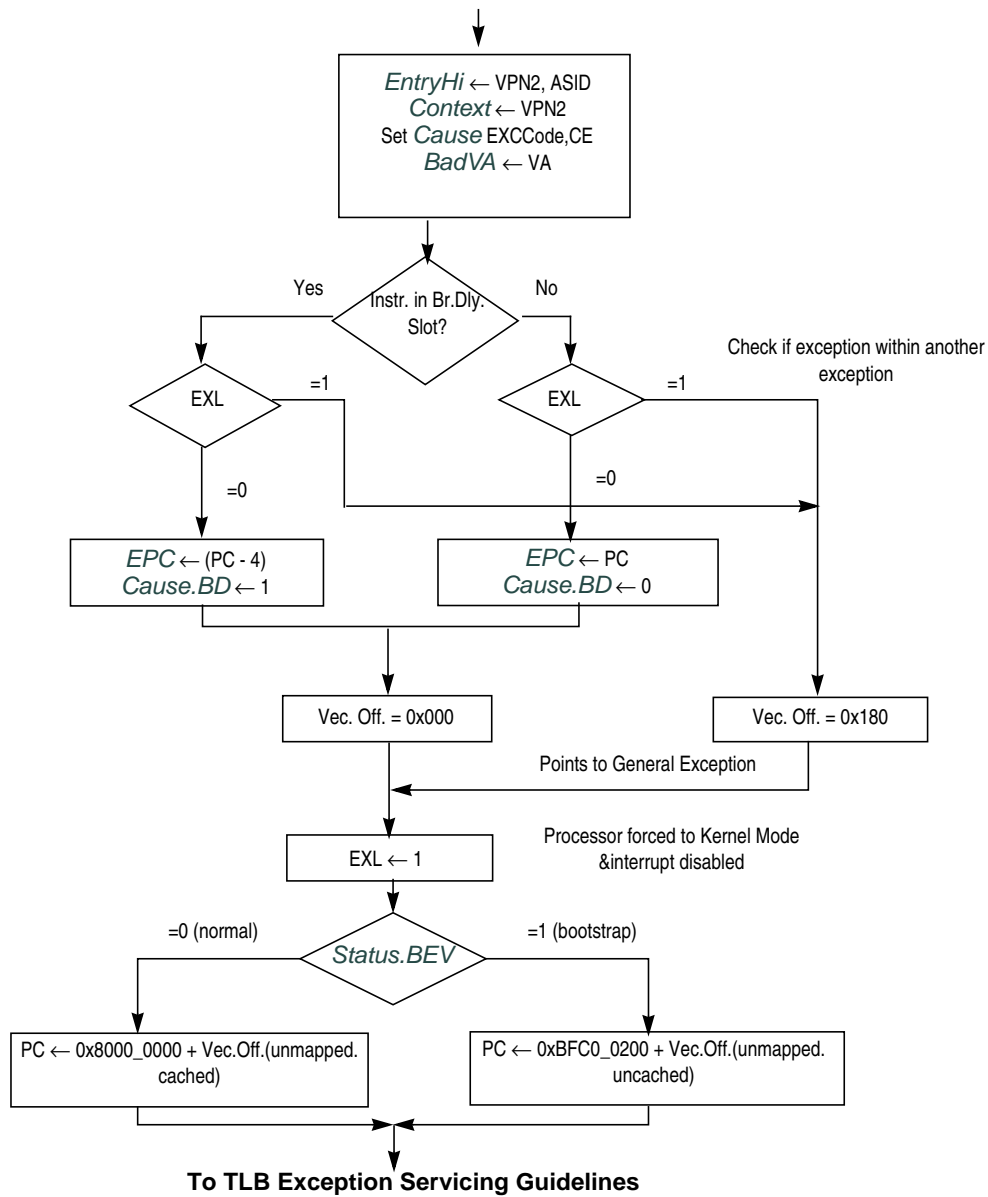


Figure 5.6 TLB Exception Servicing Guidelines (SW)

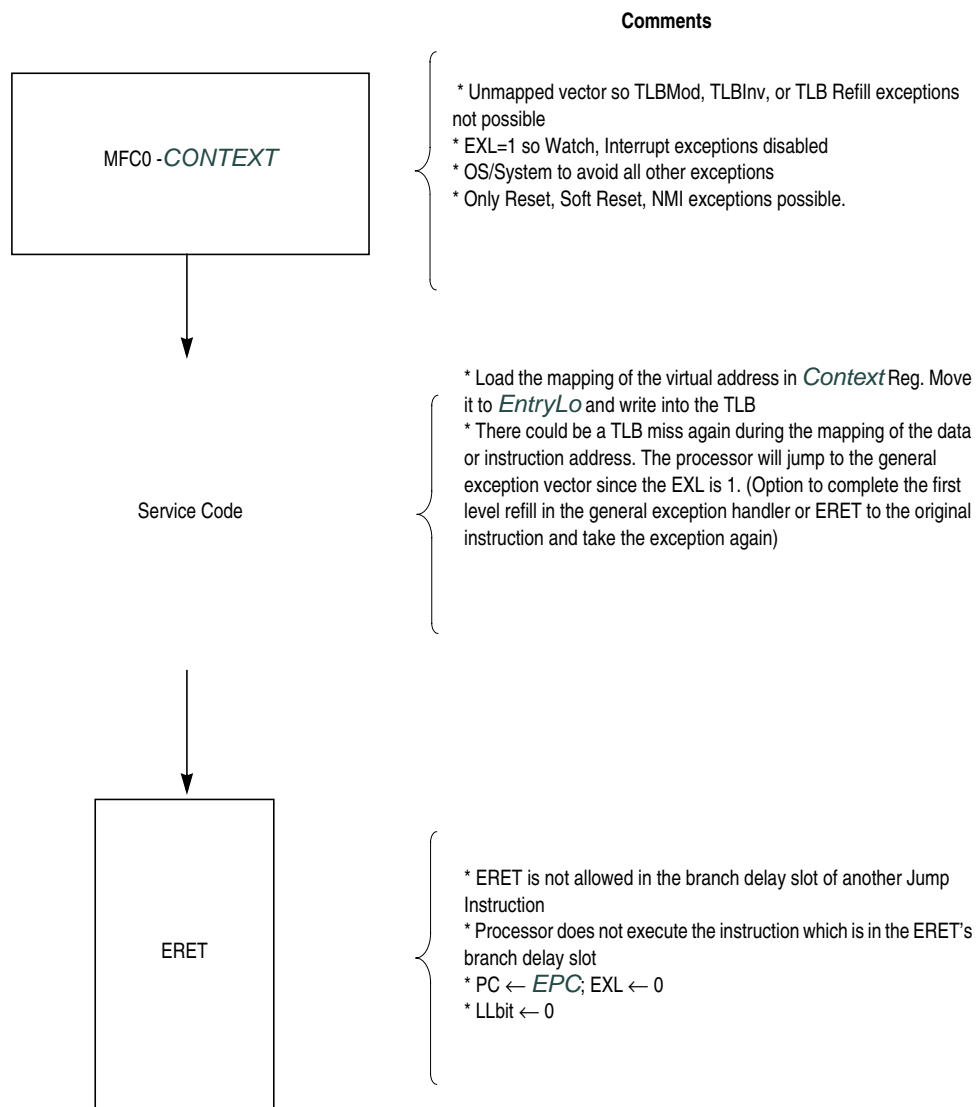
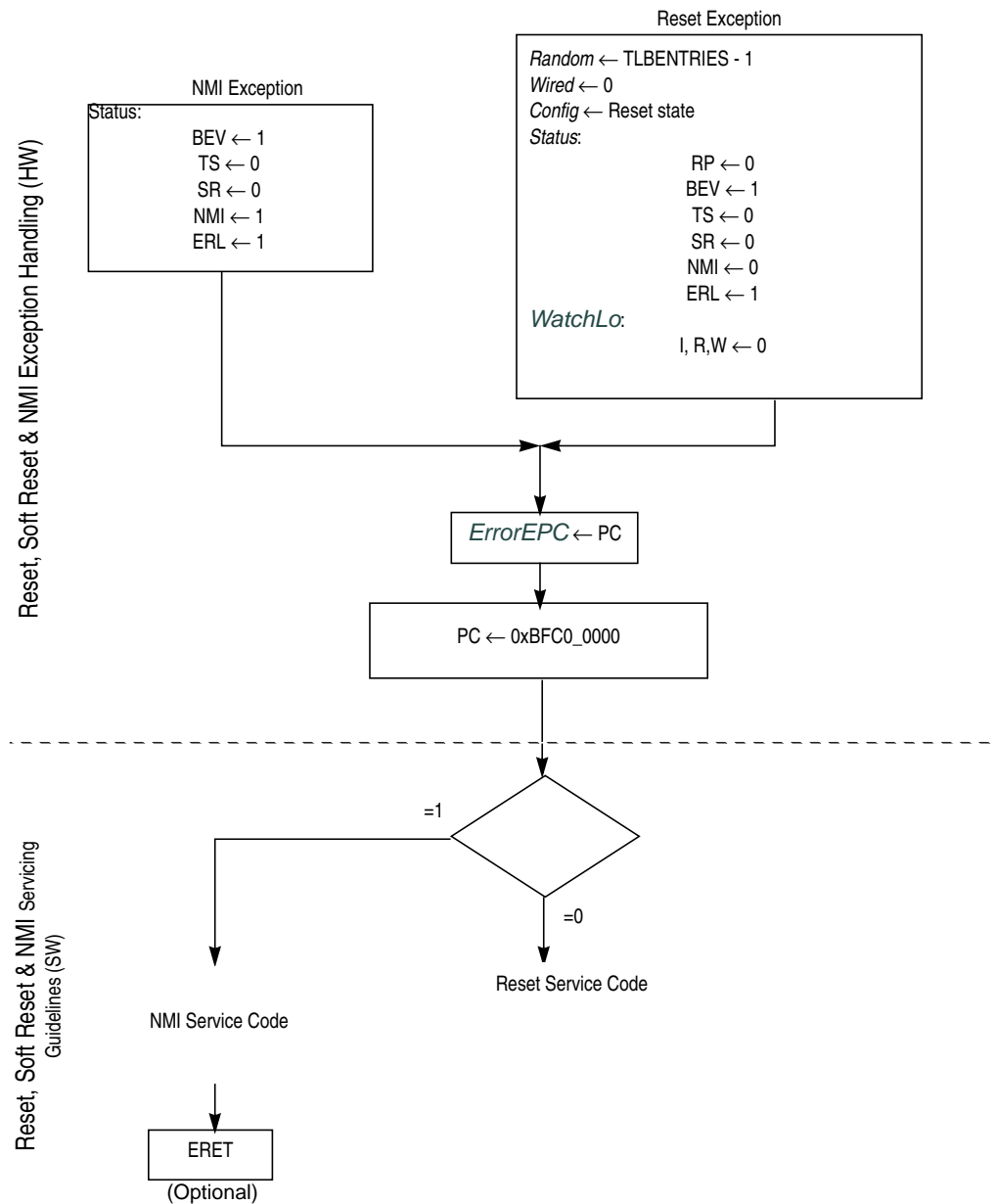


Figure 5.7 Reset and NMI Exception Handling and Servicing Guidelines



CP0 Registers of the 24K® Core

The System Control Coprocessor (CP0) provides the register interface to the 24K processor core and supports memory management, address translation, exception handling, and other privileged operations. Each CP0 register has a unique number that identifies it; this number is referred to as the *register number*. For instance, the *PageMask* register is register number 5. All registers also have a select number from 0-7, if none is specified, it is 0. After updating a CP0 register there is a hazard period of zero or more instructions from the update instruction (MTC0) and until the effect of the update has taken place in the core.

This chapter contains the following sections:

- [Section 6.1 “CP0 Register Summary”](#)
- [Section 6.2 “CP0 Register Descriptions”](#)

6.1 CP0 Register Summary

[Table 6.1](#) lists the CP0 registers in numerical order and gives a brief description. The individual registers are described throughout this chapter.

Table 6.1 CP0 Registers

| Register | | | Function | Per | | |
|----------|--------|-----------------------|--|-----|----|------|
| Number | Select | Name | | VPE | TC | Proc |
| 0 | 0 | Index ¹ | Index into the TLB array. This register is reserved if the TLB is not implemented. | X | | |
| 1 | 0 | Random ¹ | Randomly generated index into the TLB array. This register is reserved if the TLB is not implemented. | X | | |
| 2 | 0 | EntryLo0 ¹ | Low-order portion of the TLB entry for even-numbered virtual pages. This register is reserved if the TLB is not implemented. | | | |
| 3 | 0 | EntryLo1 ¹ | Low-order portion of the TLB entry for odd-numbered virtual pages. This register is reserved if the TLB is not implemented. | X | | |
| 4 | 0 | Context ² | Pointer to page table entry in memory. This register is reserved if the TLB is not implemented. | X | | |
| 4 | 2 | UserLocal | User information that can be written by privileged software and read via RDHWR register 29 | | X | |
| 5 | 0 | PageMask | PageMask controls the variable page sizes in TLB entries. This register is reserved if the TLB is not implemented. | X | | |
| 6 | 0 | Wired ¹ | Controls the number of fixed (“wired”) TLB entries. This register is reserved if the TLB is not implemented. | X | | |
| 7 | 0 | HWREna | Enables access via the RDHWR instruction to selected hardware registers in non-privileged mode. | X | | |

Table 6.1 CP0 Registers (Continued)

| Register | | | Function | Per | | |
|----------|--------|-------------------------|---|-----|----------------|------|
| Number | Select | Name | | VPE | TC | Proc |
| 8 | 0 | BadVAddr ² | Reports the address for the most recent address-related exception. | X | | |
| 9 | 0 | Count ² | Processor cycle count. | X | | |
| 10 | 0 | EntryHi ¹ | High-order portion of the TLB entry. This register is reserved if the TLB is not implemented. | X | X ³ | |
| 11 | 0 | Compare ² | Timer interrupt control. | X | | |
| 12 | 0 | Status ² | Processor status and control. | X | X ⁴ | |
| 12 | 1 | IntCtl ² | Setup for interrupt vector and interrupt priority features. | X | | |
| 12 | 2 | SRSCtl ² | Shadow register set selectors | X | | |
| 12 | 3 | SRSMap ² | In vectored interrupt mode, determines which shadow set is used for each interrupt source. | X | | |
| 13 | 0 | Cause ² | Cause of last exception. | X | | |
| 14 | 0 | EPC ² | Program counter at last exception. | X | | |
| 15 | 0 | PRId | Processor identification and revision. | X | | |
| 15 | 1 | EBase | Exception base address. | X | | |
| 16 | 0 | Config | Configuration register. | X | | |
| 16 | 1-2 | Config1-2 | Configuration for MMU, caches etc. | X | | |
| 16 | 3 | Config3 | Interrupt and ASE capabilities | X | | |
| 16 | 7 | Config7 | 24K family-specific configuration register. | X | | |
| 18 | 0-1 | WatchLo0-1 ² | Low-order watchpoint address associated with instruction watchpoints. | X | | |
| 18 | 2-3 | WatchLo2-3 ² | Low-order watchpoint address associated with data watchpoints. | X | | |
| 19 | 0-1 | WatchHi0-1 ² | High-order watchpoint address used for instruction watchpoints. | X | | |
| 19 | 2-3 | WatchHi2-3 ² | High-order watchpoint address used for data watchpoints. | X | | |
| 23 | 0 | Debug ⁵ | EJTAG Debug register. | X | | |
| 24 | 0 | DEPC ⁵ | Restart address from last EJTAG debug exception. | X | | |
| 25 | 0 | PerfCtl0 | Performance counter 0 control. | | X | |
| 25 | 1 | PerfCnt0 | Performance counter 0. | | X | |
| 25 | 2 | PerfCtl1 | Performance counter 1 control. | | X | |
| 25 | 3 | PerfCnt1 | Performance counter 1. | | X | |
| 26 | 0 | ErrCtl | Software test enable of way-select and Data RAM arrays for I-Cache and D-Cache. | X | | |
| 27 | 0 | CacheErr | Records information about cache parity errors | X | | |
| 28 | 0 | ITagLo | Cache tag read/write interface for I-cache. | X | | |
| 28 | 1 | IDataLo | Low-order data read/write interface for I-cache. | X | | |
| 28 | 2 | DTagLo | Cache tag read/write interface for D-cache. | X | | |

Table 6.1 CP0 Registers (Continued)

| Register | | | Function | Per | | |
|----------|--------|-----------------------|--|-----|----|------|
| Number | Select | Name | | VPE | TC | Proc |
| 28 | 3 | DDataLo | Low-order data read/write interface for D-cache. | X | | |
| 28 | 4 | L23TagLo | Cache tag read/write interface for L2-cache. | X | | |
| 28 | 5 | L23DataLo | Low-order data read/write interface for L2-cache. | X | | |
| 29 | 1 | IDataHi | High-order data read/write interface for I-cache. | X | | |
| 29 | 5 | L23DataHi | High-order data read/write interface for L2-cache. | X | | |
| 30 | 0 | ErrorEPC ² | Program counter at last error. | X | | |
| 31 | 0 | DeSAVE ⁵ | Debug handler scratchpad register. | X | | |

1. Registers used in memory management.

2. Registers used in exception processing.

3. *ASID* per-TC. See Section 6.2.11 “EntryHi Register (CP0 Register 10, Select 0)”.

4. *KSU* and *CU0-3* per-TC. See Section 6.2.13 “Status Register (CP0 Register 12, Select 0)”.

5. Registers used in debug.

6.2 CP0 Register Descriptions

The CP0 registers provide the interface between the ISA and the architecture. Each register is discussed below, with the registers presented in numerical order, first by register number, then by select field number.

For each register described below, field descriptions include the read/write properties of the field, and the reset state of the field. For single bit fields, the name is truncated to a single character which is then shown outside brackets in the Fields|Name column; for example, *(TLB)S* for the TLB Sharable bit in the *MVPCConf0* register. For the read/write properties of the field, the following notation is used:

Table 6.2 CP0 Register Field Types

| Notation | Hardware Interpretation | Software Interpretation |
|----------|---|--|
| R/W | <p>A field in which all bits are readable and writable by software and, potentially, by hardware. Hardware updates of this field are visible by software reads. Software updates of this field are visible by hardware reads.</p> <p>If the reset state of this field is “Undefined,” either software or hardware must initialize the value before the first read will return a predictable value. This should not be confused with the formal definition of UNDEFINED behavior.</p> | |
| R | <p>A field that is either static or is updated only by hardware.</p> <p>If the Reset State of this field is either “0” or “Preset”, hardware initializes this field to zero or to the appropriate state, respectively, on powerup.</p> <p>If the Reset State of this field is “Undefined”, hardware updates this field only under those conditions specified in the description of the field.</p> | <p>A field to which the value written by software is ignored by hardware. Software may write any value to this field without affecting hardware behavior. Software reads of this field return the last value updated by hardware.</p> <p>If the Reset State of this field is “Undefined,” software reads of this field result in an UNPREDICTABLE value except after a hardware update done under the conditions specified in the description of the field.</p> |
| W | <p>A field that can be written by software but which can not be read by software. Software reads of this field will return an UNDEFINED value.</p> | |

Table 6.2 CP0 Register Field Types (Continued)

| Notation | Hardware Interpretation | Software Interpretation |
|----------|--|---|
| 0 | A field that hardware does not update, and for which hardware can assume a zero value. | A field to which the value written by software must be zero. Software writes of non-zero values to this field may result in UNDEFINED behavior of the hardware. Software reads of this field return zero as long as all previous software writes are zero. If the Reset State of this field is “Undefined,” software must write this field with zero before it is guaranteed to read as zero. |

6.2.1 Index Register (CP0 Register 0, Select 0)

The *Index* register is a 32-bit read/write register that contains the index used to access the TLB for TLBP, TLBR, and TLBWI instructions. The width of the index field is implementation-dependent as a function of the number of TLB entries that are implemented. The minimum value for TLB-based MMUs is $\text{Ceiling}(\text{Log}_2(\text{TLBEntries}))$.

The operation of the processor is **UNDEFINED** if a value greater than or equal to the number of TLB entries is written to the *Index* register.

This register is only valid with the TLB. It is reserved if the FM is implemented.

Figure 6.1 Index Register Format

| | | | | |
|----|----|-------|---|---|
| 31 | 30 | 6 | 5 | 0 |
| P | 0 | Index | | |

Table 6.3 Index Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| P | 31 | Probe Failure. Set to 1 by hardware when the previous TLBProbe (TLBP) instruction failed to find a match in the TLB. | R/W | Undefined |
| 0 | 30:6 | Must be written as zeros; returns zeros on reads. | 0 | 0 |
| Index | 5:0 | Index to the TLB entry affected by the TLBRead and TLBWrite instructions. For 16 or 32 entry TLBs, behavior is undefined if index points to a non-existent entry. | R/W | Undefined |

6.2.2 Random Register (CP0 Register 1, Select 0)

The *Random* register is a read-only register whose value is used to index the TLB during a TLBWR instruction. The width of the Random field is calculated in the same manner as that described for the *Index* register above.

The value of the register varies between an upper and lower bound as follow:

- A lower bound is set by the number of TLB entries reserved for exclusive use by the operating system (the contents of the *Wired* register). The entry indexed by the *Wired* register is the first entry available to be written by a TLB Write Random operation.
- An upper bound is set by the total number of TLB entries minus 1.

The *Random* register is decremented by one almost every clock, wrapping after the value in the *Wired* register is reached. To enhance the level of randomness and reduce the possibility of a live lock condition, an LFSR register is used which prevents the decrement pseudo-randomly.

The processor initializes the *Random* register to the upper bound on a Reset exception and when the *Wired* register is written.

This register is only valid with the TLB. It is reserved if the FM is implemented.

Figure 6.2 Random Register Format

| | | | |
|----|--------|---|---|
| 31 | 6 | 5 | 0 |
| 0 | Random | | |

Table 6.4 Random Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-----------------|
| Name | Bit(s) | | | |
| 0 | 31:6 | Must be written as zero; returns zero on reads. | 0 | 0 |
| Random | 5:0 | TLB Random Index | R | TLB Entries - 1 |

6.2.3 EntryLo0 and EntryLo1 Registers (CP0 Registers 2 and 3, Select 0)

The pair of *EntryLo* registers act as the interface between the TLB and the TLBR, TLBWI, and TLBWR instructions. For a TLB-based MMU, *EntryLo0* holds the entries for even pages and *EntryLo1* holds the entries for odd pages. The contents of the *EntryLo0* and *EntryLo1* registers are undefined after an address error, TLB invalid, TLB modified, or TLB refill exception. These registers are only valid when the TLB-based memory management unit is present. They are reserved if the FM-style MMU is present.

Figure 6.3 EntryLo0, EntryLo1 Register Format

| | | | | | | | | | | |
|----|----|-----|----|----|---|---|---|---|---|---|
| 31 | 30 | 29 | 26 | 25 | 6 | 5 | 3 | 2 | 1 | 0 |
| R | 0 | PFN | | | | C | D | V | G | |

Table 6.5 EntryLo0, EntryLo1 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| R | 31:30 | Reserved. Should be ignored on writes; returns zero on reads. | R | 0 |

Table 6.5 EntryLo0, EntryLo1 Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| 0 | 29:26 | These 4 bits are normally part of the PFN, however, since the 24k supports only 32 bits of physical address, the PFN is only 20 bits wide; therefore, bits 29:26 of this register must be written with zeros. | R | 0 |
| PFN | 25:6 | Page Frame Number: Contributes to the definition of the high-order bits of the physical address. The PFN field corresponds to bits 31..12 of the physical address. | R/W | Undefined |
| C | 5:3 | Coherency attribute of the page. See Table 6.6. | R/W | Undefined |
| D | 2 | “Dirty” or write-enable bit: Indicates that the page has been written, and/or is writable. If this bit is a one, then stores to the page are permitted. If this bit is a zero, then stores to the page cause a TLB Modified exception. | R/W | Undefined |
| V | 1 | Valid bit: Indicates that the TLB entry, and thus the virtual page mapping are valid. If this bit is a one, then accesses to the page are permitted. If this bit is a zero, then accesses to the page cause a <i>TLB Invalid</i> exception | R/W | Undefined |
| G | 0 | Global bit: On a TLB write, the logical AND of the G bits in both the <i>EntryLo0</i> and <i>EntryLo1</i> registers become the G bit in the TLB entry. If the TLB entry G bit is a one, then the ASID comparisons are ignored during TLB matches. On a read from a TLB entry, the G bits of both <i>EntryLo0</i> and <i>EntryLo1</i> reflect the state of the TLB G bit. | R/W | Undefined |

Table 6.6 lists the encoding of the *C* field of the *EntryLo0* and *EntryLo1* registers and the *K0* field of the *Config* register.

Table 6.6 Cache Coherency Attributes

| C[5:3] Value | Cache Coherency Attribute |
|--------------|--|
| 0 | Cacheable, noncoherent, write-through, no write allocate |
| 1 | Reserved |
| 2 | Uncached |
| 3 | Cacheable, noncoherent, write-back, write allocate |
| 4,5,6 | Reserved |
| 7 | Uncached Accelerated |

6.2.4 Context Register (CP0 Register 4, Select 0)

The *Context* register is a read/write register containing a pointer to an entry in the page table entry (PTE) array. This array is an operating system data structure that stores virtual-to-physical translations. During a TLB miss, the operating system loads the TLB with the missing translation from the PTE array. The *Context* register duplicates some of the information provided in the *BadVAddr* register but is organized in such a way that the operating system can directly reference an 8-byte page table entry (PTE) in memory.

A TLB exception (TLB Refill, TLB Invalid, or TLB Modified) causes bits $VA_{31:13}$ of the virtual address to be written into the *BadVPN2* field of the *Context* register. The *PTEBase* field is written and used by the operating system.

The *BadVPN2* field of the *Context* register is not defined after an address error exception.

Figure 6.4 Context Register Format



Table 6.7 Context Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| PTEBase | 31:23 | This field is for use by the operating system and is normally written with a value that allows the operating system to use the Context Register as a pointer into the current PTE array in memory. | R/W | Undefined |
| BadVPN2 | 22:4 | This field is written by hardware on a TLB miss. It contains bits $VA_{31:13}$ of the virtual address that missed. | R | Undefined |
| 0 | 3:0 | Must be written as zero; returns zero on reads. | 0 | 0 |

6.2.5 UserLocal Register (CP0 Register 4, Select 2)

The *UserLocal* register is a read-write register that is not interpreted by the hardware and conditionally readable via the RDHWR instruction.

Figure 6.5 shows the format of the *UserLocal* register; Table 6.8 describes the *UserLocal* register fields.

Figure 6.5 UserLocal Register Format

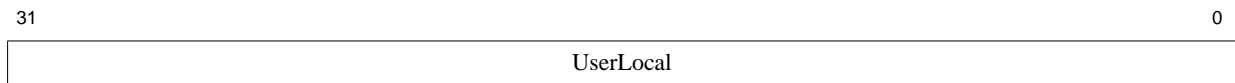


Table 6.8 UserLocal Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|-----------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| UserLocal | 31:0 | This field contains software information that is not interpreted by hardware. | R/W | Undefined |

Programming Notes

Privileged software may write this register with arbitrary information and make it accessible to unprivileged software via register 29 (ULR) of the RDHWR instruction. To do so, bit 29 of the *HWREna* register must be set to a 1 to enable unprivileged access to the register. In some operating environments, the *UserLocal* register contains a pointer to a thread-specific storage block that is obtained via the *RDHWR* register.

6.2.6 PageMask Register (CP0 Register 5, Select 0)

The *PageMask* register is a read/write register used for reading from and writing to the TLB. It holds a comparison mask that sets the variable page size for each TLB entry, as shown in [Table 6.10](#).

This register is only valid with the TLB. It is reserved if the FM is implemented.

Figure 6.6 PageMask Register Format

| | | | | | | | |
|----|------|----|--|----|----|---|---|
| 31 | 29 | 28 | | 13 | 12 | | 0 |
| 0 | Mask | | | | | 0 | |

Table 6.9 PageMask Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|-------------|---|--------------|-------------|
| Name | Bits | | | |
| 0 | 31:29, 12:0 | Ignored on write; returns zero on read. | R | 0 |
| Mask | 28:13 | The <i>Mask</i> field is a bit mask in which a “1” bit indicates that the corresponding bit of the virtual address should not participate in the TLB match. | R/W | Undefined |

Table 6.10 Values for the Mask Field of the PageMask Register

| Page Size | Bit | | | | | | | | | | | | | | | |
|------------|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 |
| 4 KBytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 KBytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 64 KBytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 256 KBytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 MByte | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 MByte | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 16 MByte | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 64 MByte | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 256 MByte | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Software may determine which page sizes are supported by writing all ones to the *PageMask* register, then reading the value back. If a pair of bits reads back as ones, the processor implements that page size. The operation of the processor is **UNDEFINED** if software loads the *Mask* field with a value other than one of those listed in [Table 6.10](#), even if the hardware returns a different value on read. Hardware may depend on this requirement in implementing hardware structures.

6.2.7 Wired Register (CP0 Register 6, Select 0)

The *Wired* register is a read/write register that specifies the boundary between the wired and random entries in the TLB as shown in Figure 6.7. The width of the *Wired* field is calculated in the same manner as that described for the *Index* register above. Wired entries are fixed, non-replaceable entries that are not overwritten by a TLBWR instruction. Wired entries can be overwritten by a TLBWI instruction.

The *Wired* register is reset to zero by a Reset exception. Writing the *Wired* register causes the *Random* register to reset to its upper bound.

The operation of the processor is undefined if a value greater than or equal to the number of TLB entries is written to the *Wired* register.

This register is only valid with a TLB. It is reserved when the FM is implemented.

Figure 6.7 Wired and Random Entries in the TLB

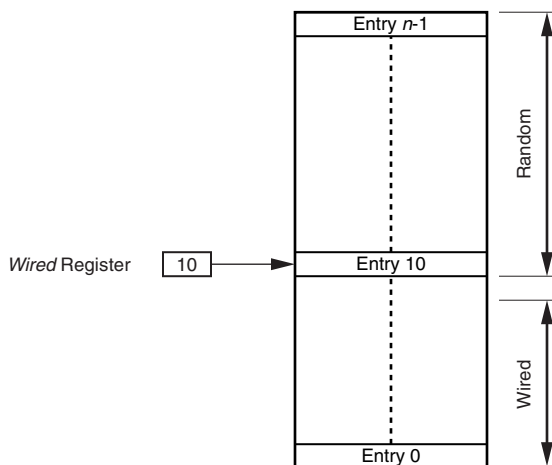


Figure 6.8 Wired Register Format

| | | | |
|----|-------|---|---|
| 31 | 6 | 5 | 0 |
| 0 | Wired | | |

Table 6.11 Wired Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| 0 | 31:6 | Must be written as zero; returns zero on reads. | 0 | 0 |
| Wired | 5:0 | TLB wired boundary. For 16 and 32 entry TLBs, behavior is undefined if value is set to a value larger than last TLB entry. | R/W | 0 |

6.2.8 HWREna Register (CP0 Register 7, Select 0)

The *HWREna* register contains a bit mask that determines which hardware registers are accessible via the RDHWR instruction when that instruction is executed in a mode in which coprocessor 0 is not enabled.

Figure 6.9 shows the format of the *HWREna* Register; Table 6.12 describes the *HWREna* register fields.

Figure 6.9 HWREna Register Format

| | | | |
|----|------|----|---|
| 31 | 30 | 29 | 0 |
| 0 | Mask | | |

Table 6.12 HWREna Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bits | | | |
| 0 | 31..30 | Reserved | 0 | 0 |
| Mask | 29..0 | Each bit in this field enables access by the RDHWR instruction to a particular hardware register (which may not be an actual register). If bit ‘n’ in this field is a 1, access is enabled to hardware register ‘n’. If bit ‘n’ of this field is a 0, access is disabled. Table 6.13 lists the RDHWR registers, and register number ‘n’ corresponds to bit ‘n’ in this field. | R/W | 0 |

Table 6.13 RDHWR Register Numbers

| Register Number | Mnemonic | Description | | | | | | | | | | |
|-----------------|---|--|-------------|---------|---|------------------------------------|---|---|---|--|------|--|
| 0 | CPUNum | This register provides read access to the coprocessor 0 <i>EBase</i> _{CPUNum} field. | | | | | | | | | | |
| 1 | SYNCL_Step | Address step size to be used with the SYNCL instruction. See that instruction’s description for the use of this value. In the typical implementation, this value should be zero if there are no caches in the system which must be synchronized (either because there are no caches, or because the instruction cache tracks writes to the data cache). In other cases, the return value should be the smallest line size of the caches that must be synchronized. For the 24K 24k, the SYNCL_Step value is 32 since the line size is 32 bytes. | | | | | | | | | | |
| 2 | CC | High-resolution cycle counter. This register provides read access to the coprocessor 0 <i>Count</i> Register. | | | | | | | | | | |
| 3 | CCRes | Resolution of the CC register. This value denotes the number of cycles between update of the register. For example: <table><tr><th>CCRes Value</th><th>Meaning</th></tr><tr><td>1</td><td>CC register increments every cycle</td></tr><tr><td>2</td><td>CC register increments every second cycle</td></tr><tr><td>3</td><td>CC register increments every third cycle</td></tr><tr><td colspan="2">etc.</td></tr></table> In the 24K 24k, the CCRes value is 2 to indicate that the CC register increments every second core cycle. | CCRes Value | Meaning | 1 | CC register increments every cycle | 2 | CC register increments every second cycle | 3 | CC register increments every third cycle | etc. | |
| CCRes Value | Meaning | | | | | | | | | | | |
| 1 | CC register increments every cycle | | | | | | | | | | | |
| 2 | CC register increments every second cycle | | | | | | | | | | | |
| 3 | CC register increments every third cycle | | | | | | | | | | | |
| etc. | | | | | | | | | | | | |
| 4-28 | | These registers numbers are reserved for future architecture use. Access results in a Reserved Instruction Exception. | | | | | | | | | | |

Table 6.13 RDHWR Register Numbers

| Register Number | Mnemonic | Description |
|-----------------|----------|--|
| 29 | ULR | User Local Register. This register provides read access to the coprocessor 0 <i>UserLocal</i> register. In some operating environments, the <i>UserLocal</i> register is a pointer to a thread-specific storage block. |
| 30-31 | | These register numbers are reserved for future implementation-dependent use. Access results in a Reserved Instruction Exception. |

Using the *HWREna* register, privileged software may select which of the hardware registers are accessible via the RDHWR instruction. In doing so, a register may be virtualized at the cost of handling a Reserved Instruction Exception, interpreting the instruction, and returning the virtualized value. For example, if it is not desirable to provide direct access to the *Count* register, access to that register may be individually disabled and the return value can be virtualized by the operating system.

Software may determine which registers are implemented by writing all ones to the *HWREna* register, then reading the value back. If a bit reads back as a one, the processor implements that hardware register.

6.2.9 BadVAddr Register (CP0 Register 8, Select 0)

The *BadVAddr* register is a read-only register that captures the most recent virtual address that caused one of the following exceptions:

- Address error (AdEL or AdES)
- TLB Refill
- TLB Invalid
- TLB Modified

The *BadVAddr* register does not capture address information for cache or bus errors, since they are not addressing errors.

Figure 6.10 BadVAddr Register Format

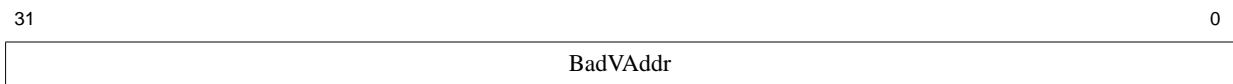


Table 6.14 BadVAddr Register Field Description

| Fields | | Description | Read / Write | Reset State |
|-----------|------|----------------------|--------------|-------------|
| Name | Bits | | | |
| Bad-VAddr | 31:0 | Bad virtual address. | R | Undefined |

6.2.10 Count Register (CP0 Register 9, Select 0)

The *Count* register acts as a timer, incrementing at a constant rate, whether or not an instruction is executed, retired, or any forward progress is made through the pipeline. If enabled, the counter increments every other clock. Setting the DC bit in the *Cause* register to 0 enables counting.

The *Count* register can be written for functional or diagnostic purposes, including at reset or to synchronize processors.

By writing the *Count_{DM}* bit in the *Debug* register, it is possible to control whether the *Count* register continues incrementing while the processor is in debug mode.

Figure 6.11 Count Register Format

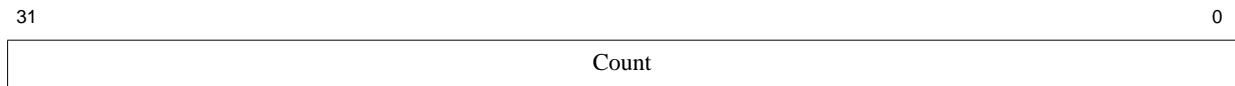


Table 6.15 Count Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|------|-------------------|--------------|-------------|
| Name | Bits | | | |
| Count | 31:0 | Interval counter. | R/W | Undefined |

6.2.11 EntryHi Register (CP0 Register 10, Select 0)

The *EntryHi* register contains the virtual address match information used for TLB read, write, and access operations.

A TLB exception (TLB Refill, TLB Invalid, or TLB Modified) causes bits $VA_{31..13}$ of the virtual address to be written into the *VPN2* field of the *EntryHi* register. A TLBR instruction writes the *EntryHi* register with the corresponding fields from the selected TLB entry. The *ASID* field is written by software with the current address space identifier value and is used during the TLB comparison process to determine TLB match.

Because the *ASID* field is overwritten by a TLBR instruction, software must save and restore the value of *ASID* around use of the TLBR. This is especially important in TLB Invalid and TLB Modified exceptions, and in other memory management software.

The *VPN2* field of the *EntryHi* register is not defined after an address error exception and this field may be modified by hardware during the address error exception sequence. Software writes of the *EntryHi* register (via MTC0) do not cause the implicit write of address-related fields in the *BadVAddr*, *Context* registers.

This register is only valid with the TLB. It is reserved if the FM is implemented.

Figure 6.12 EntryHi Register Format

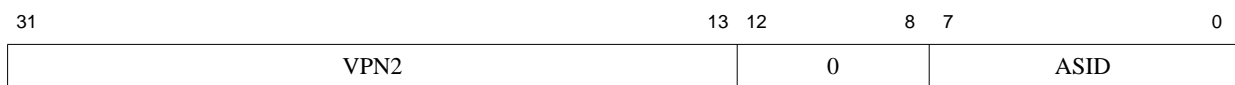


Table 6.16 EntryHi Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bits | | | |
| VPN2 | 31..13 | VA _{31..13} of the virtual address (virtual page number / 2). This field is written by hardware on a TLB exception or on a TLB read, and is written by software before a TLB write. | R/W | Undefined |
| 0 | 12..8 | Must be written as zero; returns zero on read. | 0 | 0 |
| ASID | 7..0 | Address space identifier. This field is written by hardware on a TLB read and by software to establish the current ASID value for TLB write and against which TLB references match each entry's TLB ASID field. | R/W | Undefined |

6.2.12 Compare Register (CP0 Register 11, Select 0)

The *Compare* register acts in conjunction with the *Count* register to implement a timer and timer interrupt function. The timer interrupt is an output of the cores. The *Compare* register maintains a stable value and does not change on its own.

When the value of the *Count* register equals the value of the *Compare* register, the *SI_TimerInt* pin is asserted. This pin will remain asserted until the *Compare* register is written. The *SI_TimerInt* pin can be fed back into the core on one of the interrupt pins to generate an interrupt. Traditionally, this has been done by multiplexing it with hardware interrupt 5 to set interrupt bit *IP*(7) in the *Cause* register.

For diagnostic purposes, the *Compare* register is a read/write register. In normal use, however, the *Compare* register is write-only. Writing a value to the *Compare* register, as a side effect, clears the timer interrupt.

Figure 6.13 Compare Register Format

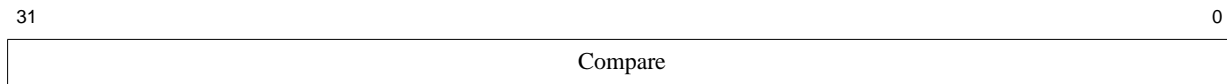


Table 6.17 Compare Register Field Description

| Fields | | Description | Read / Write | Reset State |
|---------|--------|-------------------------------|--------------|-------------|
| Name | Bit(s) | | | |
| Compare | 31:0 | Interval count compare value. | R/W | Undefined |

6.2.13 Status Register (CP0 Register 12, Select 0)

The *Status* register is a read/write register that contains the operating mode, interrupt enabling, and the diagnostic states of the processor. Fields of this register combine to create operating modes for the processor. Refer to [Section 4.2 “Modes of Operation”](#) for a discussion of operating modes, and [Section 5.3 “Interrupts”](#) for a discussion of interrupt modes.

Interrupt Enable: Interrupts are enabled when all of the following conditions are true:

- *IE* = 1

- $EXL = 0$
- $ERL = 0$
- $DM = 0$

If these conditions are met, then the settings of the IM and IE bits enable the interrupts.

6.2.13.1 Operating Modes

Debug Mode

The processor is operating in Debug Mode if the DM bit in the CP0 *Debug* register is a one. If the processor is running in Debug Mode, it has full access to all resources that are available to Kernel Mode operation.

Kernel Mode

The processor is operating in Kernel Mode when the DM bit in the *Debug* register is a zero and any of the following three conditions is true:

- The KSU field in the CP0 *Status* register contains 2#00
- The EXL bit in the *Status* register is one
- The ERL bit in the *Status* register is one

The processor enters Kernel Mode at power-up, or as the result of an interrupt, exception, or error. The processor leaves Kernel Mode and enters User Mode or Supervisor Mode when all of the previous three conditions are false, usually as the result of an ERET instruction.

Supervisor Mode

The processor is operating in Supervisor Mode when all of the following conditions are true:

- The DM bit in the *Debug* register is a zero
- The KSU field in the *Status* register contains 2#01
- The EXL and ERL bits in the *Status* register are both zero

Supervisor mode is not supported with the Fixed Mapping MMU.

User Mode

The processor is operating in User Mode when all of the following conditions are true:

- The DM bit in the *Debug* register is a zero
- The KSU field in the *Status* register contains 2#10
- The EXL and ERL bits in the *Status* register are both zero

6.2.13.2 Coprocessor Accessibility

The *Status* register CU bits control coprocessor accessibility. If any coprocessor is unusable, then an instruction that accesses it generates an exception.

Figure 6.14 Status Register Format

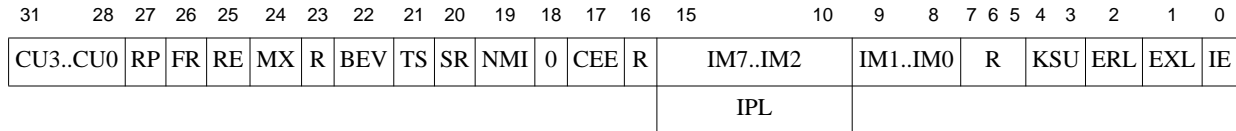


Table 6.18 Status Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|--------------------|--|--------------|-------------|---|--------------------|---|----------------|-----|-----------|
| Name | Bits | | | | | | | | | |
| CU3 | 31 | Reserved. | R | 0 | | | | | | |
| CU2 | 30 | <div>Controls access to Coprocessor 2</div> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Access not allowed</td></tr><tr><td>1</td><td>Access allowed</td></tr></table> <div>This bit can only be written when a coprocessor 2 unit is present. This bit cannot be written and will read as 0 if coprocessor 2 unit is not presen.</div> | Encoding | Meaning | 0 | Access not allowed | 1 | Access allowed | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Access not allowed | | | | | | | | | |
| 1 | Access allowed | | | | | | | | | |
| CU1 | 29 | <div>Controls access to Coprocessor 1</div> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Access not allowed</td></tr><tr><td>1</td><td>Access allowed</td></tr></table> <div>This bit can only be written when the Floating Point Unit is present (24Kf core); in the 24Kc core, this bit cannot be written and will read as 0.</div> | Encoding | Meaning | 0 | Access not allowed | 1 | Access allowed | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Access not allowed | | | | | | | | | |
| 1 | Access allowed | | | | | | | | | |
| CU0 | 28 | <div>Controls access to coprocessor 0</div> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Access not allowed</td></tr><tr><td>1</td><td>Access allowed</td></tr></table> <div>Coprocessor 0 is always usable when the processor is running in kernel mode, independent of the state of the CU0 bit.</div> | Encoding | Meaning | 0 | Access not allowed | 1 | Access allowed | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Access not allowed | | | | | | | | | |
| 1 | Access allowed | | | | | | | | | |
| RP | 27 | Enables reduced power mode. The state of the <i>RP</i> bit is available on the external 24k interface as the <i>SI_RP</i> signal. | R/W | 0 | | | | | | |

Table 6.18 Status Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|---|---|--|--------------|------------------------|--|---------|---|--|---|---|
| Name | Bits | | | | | | | | | |
| FR | 26 | This bit is used to control the floating point register mode for 64-bit floating point units: | R/W | 0 | | | | | | |
| | | <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Floating point registers can contain any 32-bit datatype. 64-bit datatypes are stored in even-odd pairs of registers</td></tr><tr><td>1</td><td>Floating point registers can contain any datatype</td></tr></table> | | | Encoding | Meaning | 0 | Floating point registers can contain any 32-bit datatype. 64-bit datatypes are stored in even-odd pairs of registers | 1 | Floating point registers can contain any datatype |
| | | Encoding | | | Meaning | | | | | |
| | | 0 | | | Floating point registers can contain any 32-bit datatype. 64-bit datatypes are stored in even-odd pairs of registers | | | | | |
| 1 | Floating point registers can contain any datatype | | | | | | | | | |
| This bit must be ignored on write and read as zero under the following conditions | | | | | | | | | | |
| <ul style="list-style-type: none">• No floating point unit is implemented• 64-bit floating point unit is not implemented | | | | | | | | | | |
| RE | 25 | Used to enable reverse-endian memory references while the processor is running in user mode Not supported | R | 0 | | | | | | |
| MX | 24 | Enables access to DSP ASE resources. An attempt to execute any DSP ASE instruction before this bit has been set to 1 will cause a DSP State Disabled exception. Since the DSP ASE is not present on the 24K core, this field is always 0. | R | 0 | | | | | | |
| R | 23 | Reserved. This field is ignored on write and read as 0. | R | 0 | | | | | | |
| BEV | 22 | Controls the location of exception vectors: | R/W | 1 | | | | | | |
| | | <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Normal</td></tr><tr><td>1</td><td>Bootstrap</td></tr></table> | | | Encoding | Meaning | 0 | Normal | 1 | Bootstrap |
| | | Encoding | | | Meaning | | | | | |
| 0 | Normal | | | | | | | | | |
| 1 | Bootstrap | | | | | | | | | |
| | | | | | | | | | | |
| TS | 21 | TLB shutdown. Indicates that a machine check exception was taken due to a TLBWI or TLBWR that would have created conflicting TLB entries. This bit is reserved if the TLB is not implemented. Software can only write a 0 to this bit to clear it and cannot force a 0-1 transition. | R/W0 | 0 | | | | | | |
| SR | 20 | Indicates that the entry through the reset exception vector was due to a Soft Reset. Soft Reset is not supported on this processor and this bit is not writeable and will always read as 0 | R | 0 | | | | | | |
| NMI | 19 | Indicates that the entry through the reset exception vector was due to an NMI: | R/W0 | 1 for NMI; 0 otherwise | | | | | | |
| | | <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Not NMI (Reset)</td></tr><tr><td>1</td><td>NMI</td></tr></table> | | | Encoding | Meaning | 0 | Not NMI (Reset) | 1 | NMI |
| | | Encoding | | | Meaning | | | | | |
| | | 0 | | | Not NMI (Reset) | | | | | |
| 1 | NMI | | | | | | | | | |
| Software can only write a 0 to this bit to clear it and cannot force a 0-1 transition. | | | | | | | | | | |
| | | | | | | | | | | |
| 0 | 18 | Must be written as zero; returns zero on read. | 0 | 0 | | | | | | |

Table 6.18 Status Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|----------------------------|--|--------------|-------------|---|----------------------------|---|---------------------------|-----|-----------|
| Name | Bits | | | | | | | | | |
| CEE | 17 | CorExtend Enable: This bit is sent to the CorExtend block to be used to enable the CorExtend block. The usage of this signal by a CorExtend block is implementation dependent. This bit is reserved if CorExtend is not present. | R/W | Undefined | | | | | | |
| R | 16 | Reserved. Ignored on write and read as zero. | R | 0 | | | | | | |
| IM7..IM2 | 15..10 | <p>Interrupt Mask: Controls the enabling of each of the hardware interrupts. Refer to Section 5.3 “Interrupts” for a complete discussion of enabled interrupts.</p> <p>An interrupt is taken if interrupts are enabled and the corresponding bits are set in both the Interrupt Mask field of the <i>Status</i> register and the Interrupt Pending field of the <i>Cause</i> register and the <i>IE</i> bit is set in the <i>Status</i> register.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Interrupt request disabled</td></tr><tr><td>1</td><td>Interrupt request enabled</td></tr></table> <p>In implementations of Release 2 of the Architecture in which EIC interrupt mode is enabled (<i>Config3</i>_{VEIC} = 1), these bits take on a different meaning and are interpreted as the <i>IPL</i> field, described below.</p> | Encoding | Meaning | 0 | Interrupt request disabled | 1 | Interrupt request enabled | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Interrupt request disabled | | | | | | | | | |
| 1 | Interrupt request enabled | | | | | | | | | |
| IPL | 15..10 | <p>Interrupt Priority Level: In implementations of Release 2 of the Architecture in which EIC interrupt mode is enabled (<i>Config3</i>_{VEIC} = 1), this field is the encoded (0..63) value of the current IPL. An interrupt will be signaled only if the requested IPL is higher than this value.</p> <p>If EIC interrupt mode is not enabled (<i>Config3</i>_{VEIC} = 0), these bits take on a different meaning and are interpreted as the <i>IM7..IM2</i> bits, described above.</p> | R/W | Undefined | | | | | | |
| IM1..IM0 | 9..8 | <p>Interrupt Mask: Controls the enabling of each of the software interrupts. Refer to Section 5.3 “Interrupts” for a complete discussion of enabled interrupts.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Interrupt request disabled</td></tr><tr><td>1</td><td>Interrupt request enabled</td></tr></table> <p>In implementations of Release 2 of the Architecture in which EIC interrupt mode is enabled (<i>Config3</i>_{VEIC} = 1), these bits are writable, but have no effect on the interrupt system.</p> | Encoding | Meaning | 0 | Interrupt request disabled | 1 | Interrupt request enabled | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Interrupt request disabled | | | | | | | | | |
| 1 | Interrupt request enabled | | | | | | | | | |
| R | 7..5 | Reserved. This field is ignored on write and read as 0. | R | 0 | | | | | | |

Table 6.18 Status Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|----------|------------------------------|--|--------------|-------------|----|--------------------------|----|------------------------------|-----|------------------------|----|----------|-----|-----------|
| Name | Bits | | | | | | | | | | | | | |
| KSU | 4..3 | <p>This field denotes the base operating mode of the processor. See Section 4.2 “Modes of Operation” for a full discussion of operating modes. The encoding of this field is:</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>00</td><td>Base mode is Kernel Mode</td></tr><tr><td>01</td><td>Base mode is Supervisor Mode</td></tr><tr><td>10</td><td>Base mode is User Mode</td></tr><tr><td>11</td><td>Reserved</td></tr></table> <p>Note that the processor can also be in kernel mode if <i>ERL</i> or <i>EXL</i> is set, regardless of the state of the <i>KSU</i> field.</p> | Encoding | Meaning | 00 | Base mode is Kernel Mode | 01 | Base mode is Supervisor Mode | 10 | Base mode is User Mode | 11 | Reserved | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | | | | | |
| 00 | Base mode is Kernel Mode | | | | | | | | | | | | | |
| 01 | Base mode is Supervisor Mode | | | | | | | | | | | | | |
| 10 | Base mode is User Mode | | | | | | | | | | | | | |
| 11 | Reserved | | | | | | | | | | | | | |
| ERL | 2 | <p>Error Level; Set by the processor when a Reset, Soft Reset, NMI or Cache Error exception are taken.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Normal level</td></tr><tr><td>1</td><td>Error level</td></tr></table> <p>When <i>ERL</i> is set:</p> <ul style="list-style-type: none">• The processor is running in kernel mode• Interrupts are disabled• The ERET instruction will use the return address held in <i>ErrorEPC</i> instead of <i>EPC</i>• The lower 2²⁹ bytes of kuseg are treated as an unmapped and uncached region. See Chapter 4, “Memory Management of the 24K® Core” on page 87. This allows main memory to be accessed in the presence of cache errors. The operation of the processor is UNDEFINED if the ERL bit is set while the processor is executing instructions from kuseg. | Encoding | Meaning | 0 | Normal level | 1 | Error level | R/W | 1 | | | | |
| Encoding | Meaning | | | | | | | | | | | | | |
| 0 | Normal level | | | | | | | | | | | | | |
| 1 | Error level | | | | | | | | | | | | | |
| EXL | 1 | <p>Exception Level; Set by the processor when any exception other than Reset, Soft Reset, or NMI exceptions is taken.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Normal level</td></tr><tr><td>1</td><td>Exception level</td></tr></table> <p>When <i>EXL</i> is set:</p> <ul style="list-style-type: none">• The processor is running in Kernel Mode• Interrupts are disabled.• TLB Refill exceptions use the general exception vector instead of the TLB Refill vector.• <i>EPC</i>, <i>CauseBD</i> and <i>SRSCtl</i> (implementations of Release 2 of the Architecture only) will not be updated if another exception is taken | Encoding | Meaning | 0 | Normal level | 1 | Exception level | R/W | Undefined | | | | |
| Encoding | Meaning | | | | | | | | | | | | | |
| 0 | Normal level | | | | | | | | | | | | | |
| 1 | Exception level | | | | | | | | | | | | | |

Table 6.18 Status Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|-------------------------|--|--------------|-------------|---|-------------------------|---|------------------------|-----|-----------|
| Name | Bits | | | | | | | | | |
| IE | 0 | <div>Interrupt Enable: Acts as the master enable for software and hardware interrupts:</div> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Interrupts are disabled</td></tr><tr><td>1</td><td>Interrupts are enabled</td></tr></table> <div>In Release 2 of the Architecture, this bit may be modified separately via the DI and EI instructions.</div> | Encoding | Meaning | 0 | Interrupts are disabled | 1 | Interrupts are enabled | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Interrupts are disabled | | | | | | | | | |
| 1 | Interrupts are enabled | | | | | | | | | |

6.2.14 IntCtl Register (CP0 Register 12, Select 1)

The *IntCtl* register controls the expanded interrupt capability added in Release 2 of the Architecture, including vectored interrupts and support for an external interrupt controller. This register does not exist in implementations of Release 1 of the Architecture.

Figure 6.15 IntCtl Register Format

| | | | | | | | | | |
|------|-------|----|----|----|----|---|----|---|---|
| 31 | 29 | 28 | 26 | 25 | 10 | 9 | 5 | 4 | 0 |
| IPTI | IPPCI | 0 | | | | | VS | 0 | |

Table 6.19 IntCtl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | | |
|----------|--------|---|--------------|-------------|---------------------------|---|---|-----|---|---|-----|---|---|-----|---|---|-----|---|---|-----|---|---|-----|---|----------------|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | | | | |
| IPTI | 31:29 | <p>For Interrupt Compatibility and Vectored Interrupt modes, this field specifies the IP number to which the Timer Interrupt request is merged, and allows software to determine whether to consider <i>Cause_{TI}</i> for a potential interrupt.</p> <table><tr><th>Encoding</th><th>IP bit</th><th>Hardware Interrupt Source</th></tr><tr><td>2</td><td>2</td><td>HW0</td></tr><tr><td>3</td><td>3</td><td>HW1</td></tr><tr><td>4</td><td>4</td><td>HW2</td></tr><tr><td>5</td><td>5</td><td>HW3</td></tr><tr><td>6</td><td>6</td><td>HW4</td></tr><tr><td>7</td><td>7</td><td>HW5</td></tr></table> <p>The value of this bit is set by the static input, <i>SI_IPTI</i>[2:0]. This allows external logic to communicate the specific <i>SI_Int</i> hardware interrupt pin to which the <i>SI_TimerInt</i> signal is attached. The value of this field is not meaningful if External Interrupt Controller Mode is enabled. The external interrupt controller is expected to provide this information for that interrupt mode.</p> | Encoding | IP bit | Hardware Interrupt Source | 2 | 2 | HW0 | 3 | 3 | HW1 | 4 | 4 | HW2 | 5 | 5 | HW3 | 6 | 6 | HW4 | 7 | 7 | HW5 | R | Externally Set |
| Encoding | IP bit | Hardware Interrupt Source | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2 | HW0 | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 3 | HW1 | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | 4 | HW2 | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | 5 | HW3 | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 6 | HW4 | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 7 | HW5 | | | | | | | | | | | | | | | | | | | | | | | |

Table 6.19 IntCtl Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | | |
|----------|------------|--|-------------------------------|-----------------------------------|-----------------------------------|--------|---------------------------|---|-------|--------|----|-------|--------|----|-------|--------|-----|-------|--------|-----|-------|--------|-----|---|-----|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | | | | |
| IPPCI | 28:26 | For Interrupt Compatibility and Vectored Interrupt modes, this field specifies the IP number to which the Performance Counter Interrupt request is merged, and allows software to determine whether to consider <i>Cause_{PCI}</i> for a potential interrupt. | R | Externally Set | | | | | | | | | | | | | | | | | | | | | |
| | | <table><tr><th>Encoding</th><th>IP bit</th><th>Hardware Interrupt Source</th></tr><tr><td>2</td><td>2</td><td>HW0</td></tr><tr><td>3</td><td>3</td><td>HW1</td></tr><tr><td>4</td><td>4</td><td>HW2</td></tr><tr><td>5</td><td>5</td><td>HW3</td></tr><tr><td>6</td><td>6</td><td>HW4</td></tr><tr><td>7</td><td>7</td><td>HW5</td></tr></table> <p>The value of this bit is set by the static input, <i>SI_IPPCI</i>[2:0]. This allows external logic to communicate the specific <i>SI_Int</i> hardware interrupt pin to which the <i>SI_PCInt</i> signal is attached.</p> <p>The value of this field is not meaningful if External Interrupt Controller Mode is enabled. The external interrupt controller is expected to provide this information for that interrupt mode.</p> | | | Encoding | IP bit | Hardware Interrupt Source | 2 | 2 | HW0 | 3 | 3 | HW1 | 4 | 4 | HW2 | 5 | 5 | HW3 | 6 | 6 | HW4 | 7 | 7 | HW5 |
| Encoding | IP bit | Hardware Interrupt Source | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2 | HW0 | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 3 | HW1 | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | 4 | HW2 | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | 5 | HW3 | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 6 | HW4 | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 7 | HW5 | | | | | | | | | | | | | | | | | | | | | | | |
| VS | 9:5 | Vector Spacing. If vectored interrupts are implemented (as denoted by <i>Config3_{VInt}</i> or <i>Config3_{VEIC}</i>), this field specifies the spacing between vectored interrupts. | R/W | 0 | | | | | | | | | | | | | | | | | | | | | |
| | | <table><tr><th>Encoding</th><th>Spacing Between Vectors (hex)</th><th>Spacing Between Vectors (decimal)</th></tr><tr><td>16#00</td><td>16#000</td><td>0</td></tr><tr><td>16#01</td><td>16#020</td><td>32</td></tr><tr><td>16#02</td><td>16#040</td><td>64</td></tr><tr><td>16#04</td><td>16#080</td><td>128</td></tr><tr><td>16#08</td><td>16#100</td><td>256</td></tr><tr><td>16#10</td><td>16#200</td><td>512</td></tr></table> <p>All other values are reserved. The operation of the processor is UNDEFINED if a reserved value is written to this field.</p> | Encoding | Spacing Between Vectors (hex) | Spacing Between Vectors (decimal) | 16#00 | 16#000 | 0 | 16#01 | 16#020 | 32 | 16#02 | 16#040 | 64 | 16#04 | 16#080 | 128 | 16#08 | 16#100 | 256 | 16#10 | 16#200 | 512 | | |
| | | Encoding | Spacing Between Vectors (hex) | Spacing Between Vectors (decimal) | | | | | | | | | | | | | | | | | | | | | |
| 16#00 | 16#000 | 0 | | | | | | | | | | | | | | | | | | | | | | | |
| 16#01 | 16#020 | 32 | | | | | | | | | | | | | | | | | | | | | | | |
| 16#02 | 16#040 | 64 | | | | | | | | | | | | | | | | | | | | | | | |
| 16#04 | 16#080 | 128 | | | | | | | | | | | | | | | | | | | | | | | |
| 16#08 | 16#100 | 256 | | | | | | | | | | | | | | | | | | | | | | | |
| 16#10 | 16#200 | 512 | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 25:10, 4:0 | Must be written as zero; returns zero on read. | | | | | | | | | | | | | | | | | | | | | | | |
| | | | 0 | 0 | | | | | | | | | | | | | | | | | | | | | |

6.2.15 SRSCtl Register (CP0 Register 12, Select 2)

The *SRSCtl* register controls the operation of GPR shadow sets in the processor.

Figure 6.16 SRSCtl Register Format

| | | | | | | | | | | | | | | | | | | | |
|----|----|-----|----|----|----|-------|----|----|----|-----|----|----|----|-----|---|---|---|-----|---|
| 31 | 30 | 29 | 26 | 25 | 22 | 21 | 18 | 17 | 16 | 15 | 12 | 11 | 10 | 9 | 6 | 5 | 4 | 3 | 0 |
| 0 | | HSS | | 0 | | EICSS | | 0 | | ESS | | 0 | | PSS | | 0 | | CSS | |

Table 6.20 SRSCtl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|----------|---|--|--------------|-------------|---|---|---|------------------------------|---|-------------------------------|---------|----------|---|--------|
| Name | Bits | | | | | | | | | | | | | |
| HSS | 29:26 | <p>Highest Shadow Set. This field contains the highest shadow set number that is implemented by this processor. A value of zero in this field indicates that only the normal GPRs are implemented. Possible values of this field for the 24K processor are:</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>One shadow set (normal GPR set) is present.</td></tr><tr><td>1</td><td>Two shadow sets are present.</td></tr><tr><td>3</td><td>Four shadow sets are present.</td></tr><tr><td>2, 3-15</td><td>Reserved</td></tr></table> <p>The value in this field also represents the highest value that can be written to the <i>ESS</i>, <i>EICSS</i>, <i>PSS</i>, and <i>CSS</i> fields of this register, or to any of the fields of the <i>SRSSMap</i> register. The operation of the processor is UNDEFINED if a value larger than the one in this field is written to any of these other fields.</p> | Encoding | Meaning | 0 | One shadow set (normal GPR set) is present. | 1 | Two shadow sets are present. | 3 | Four shadow sets are present. | 2, 3-15 | Reserved | R | Preset |
| Encoding | Meaning | | | | | | | | | | | | | |
| 0 | One shadow set (normal GPR set) is present. | | | | | | | | | | | | | |
| 1 | Two shadow sets are present. | | | | | | | | | | | | | |
| 3 | Four shadow sets are present. | | | | | | | | | | | | | |
| 2, 3-15 | Reserved | | | | | | | | | | | | | |
| EICSS | 21:18 | <p>EIC interrupt mode shadow set. If <i>Config3_{VEIC}</i> is 1 (EIC interrupt mode is enabled), this field is loaded from the external interrupt controller for each interrupt request and is used in place of the <i>SRSSMap</i> register to select the current shadow set for the interrupt. See Section 5.3.1.3 “External Interrupt Controller Mode” for a discussion of EIC interrupt mode. If <i>Config3_{VEIC}</i> is 0, this field returns zero on read.</p> | R | Undefined | | | | | | | | | | |
| ESS | 15:12 | <p>Exception Shadow Set. This field specifies the shadow set to use on entry to Kernel Mode caused by any exception other than a vectored interrupt.</p> <p>The operation of the processor is UNDEFINED if software writes a value into this field that is greater than the value in the <i>HSS</i> field.</p> | R/W | 0 | | | | | | | | | | |
| PSS | 9:6 | <p>Previous Shadow Set. If GPR shadow registers are implemented, and with the exclusions noted in the next paragraph, this field is copied from the <i>CSS</i> field when an exception or interrupt occurs. An ERET instruction copies this value back into the <i>CSS</i> field if <i>Status_{BEV}</i> = 0.</p> <p>This field is not updated on any exception which sets <i>Status_{ERL}</i> to 1 (i.e., Reset, Soft Reset, NMI, cache error), an entry into EJTAG Debug mode, or any exception or interrupt that occurs with <i>Status_{EXL}</i> = 1, or <i>Status_{BEV}</i> = 1. This field is not updated on an exception that occurs while <i>Status_{ERL}</i> = 1.</p> <p>The operation of the processor is UNDEFINED if software writes a value into this field that is greater than the value in the <i>HSS</i> field.</p> | R/W | 0 | | | | | | | | | | |

Table 6.20 SRSCtl Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|--|--|--------------|-------------|
| Name | Bits | | | |
| CSS | 3:0 | Current Shadow Set. If GPR shadow registers are implemented, this field is the number of the current GPR set. With the exclusions noted in the next paragraph, this field is updated with a new value on any interrupt or exception, and restored from the PSS field on an ERET. Table 6.21 describes the various sources from which the CSS field is updated on an exception or interrupt. This field is not updated on any exception which sets <i>Status_{ERL}</i> to 1 (i.e., Reset, Soft Reset, NMI, cache error), an entry into EJTAG Debug mode, or any exception or interrupt that occurs with <i>Status_{EXL}</i> = 1, or <i>Status_{BEV}</i> = 1. Neither is it updated on an ERET with <i>Status_{ERL}</i> = 1 or <i>Status_{BEV}</i> = 1. This field is not updated on an exception that occurs while <i>Status_{ERL}</i> = 1. The value of CSS can be changed directly by software only by writing the PSS field and executing an ERET instruction. | R | 0 |
| 0 | 31:30, 25:22, 17:16, 11:10, 5:4 | Must be written as zeros; returns zero on read. | 0 | 0 |

Table 6.21 Sources for new SRSCtl_{CSS} on an Exception or Interrupt

| Exception Type | Condition | SRSCtl _{CSS} Source | Comment |
|------------------------|---|----------------------------------|--|
| Exception | All | <i>SRSCtl_{ESS}</i> | |
| Non-Vectored Interrupt | <i>Cause_{IV}</i> = 0 | <i>SRSCtl_{ESS}</i> | Treat as exception |
| Vectored Interrupt | <i>Cause_{IV}</i> = 1 and <i>Config3_{VEIC}</i> = 0 and <i>Config3_{VInt}</i> = 1 | <i>SRSSMap_{VECTNUM}</i> | Source is internal map register. (for VECTNUM see Table 5.4) |
| Vectored EIC Interrupt | <i>Cause_{IV}</i> = 1 and <i>Config3_{VEIC}</i> = 1 | <i>SRSCtl_{EICSS}</i> | Source is external interrupt controller. |

6.2.16 SRSSMap Register (CP0 Register 12, Select 3)

The *SRSSMap* register contains 8 4-bit fields that provide the mapping from an vector number to the shadow set number to use when servicing such an interrupt. The values from this register are not used for a non-interrupt exception, or a non-vectored interrupt (*Cause_{IV}* = 0 or *IntCtl_{VS}* = 0). In such cases, the shadow set number comes from *SRSCtl_{ESS}*.

If *SRSCtl_{HSS}* is zero, the results of a software read or write of this register are **UNPREDICTABLE**.

The operation of the processor is **UNDEFINED** if a value is written to any field in this register that is greater than the value of *SRSCtl_{HSS}*.

The *SRSMap* register contains the shadow register set numbers for vector numbers 7..0. The same shadow set number can be established for multiple interrupt vectors, creating a many-to-one mapping from a vector to a single shadow register set number.

Figure 6.17 SRSMap Register Format

| | | | | | | | | | | | | | | | |
|------|------|------|------|------|------|------|------|----|----|----|---|---|---|---|---|
| 31 | 28 | 27 | 24 | 23 | 20 | 19 | 16 | 15 | 12 | 11 | 8 | 7 | 4 | 3 | 0 |
| SSV7 | SSV6 | SSV5 | SSV4 | SSV3 | SSV2 | SSV1 | SSV0 | | | | | | | | |

Table 6.22 SRSMap Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bits | | | |
| SSV7 | 31..28 | Shadow register set number for Vector Number 7 | R/W | 0 |
| SSV6 | 27..24 | Shadow register set number for Vector Number 6 | R/W | 0 |
| SSV5 | 23..20 | Shadow register set number for Vector Number 5 | R/W | 0 |
| SSV4 | 19..16 | Shadow register set number for Vector Number 4 | R/W | 0 |
| SSV3 | 15..12 | Shadow register set number for Vector Number 3 | R/W | 0 |
| SSV2 | 11..8 | Shadow register set number for Vector Number 2 | R/W | 0 |
| SSV1 | 7..4 | Shadow register set number for Vector Number 1 | R/W | 0 |
| SSV0 | 3..0 | Shadow register set number for Vector Number 0 | R/W | 0 |

6.2.17 Cause Register (CP0 Register 13, Select 0)

The *Cause* register primarily describes the cause of the most recent exception. In addition, fields also control software interrupt requests and the vector through which interrupts are dispatched. With the exception of the *IP1..0*, *DC*, *IV*, and *WP* fields, all fields in the *Cause* register are read-only. Release 2 of the Architecture added optional support for an External Interrupt Controller (EIC) interrupt mode, in which *IP7..2* are interpreted as the Requested Interrupt Priority Level (RIPL).

Figure 6.18 Cause Register Format

| | | | | | | | | | | | | | | | | | | | | |
|----|----|----|----|-----|----|----|----|----|----------|----------|----|----------|----|---|---|---|---|---|---|---|
| 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 16 | 15 | 10 | 9 | 8 | 7 | 6 | 2 | 1 | 0 |
| BD | TI | CE | DC | PCI | 0 | IV | WP | 0 | IP7..IP2 | IP1..IP0 | 0 | Exc Code | 0 | | | | | | | |
| | | | | | | | | | RIPL | | | | | | | | | | | |

Table 6.23 Cause Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|---|---|--------------|-------------|---|---|---|---|-----|-----------|
| Name | Bits | | | | | | | | | |
| BD | 31 | <p>Indicates whether the last exception taken occurred in a branch delay slot:</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Not in delay slot</td></tr><tr><td>1</td><td>In delay slot</td></tr></table> <p>The processor updates <i>BD</i> only if <i>Status_{EXL}</i> was zero when the exception occurred.</p> | Encoding | Meaning | 0 | Not in delay slot | 1 | In delay slot | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Not in delay slot | | | | | | | | | |
| 1 | In delay slot | | | | | | | | | |
| TI | 30 | <p>Timer Interrupt. This bit denotes whether a timer interrupt is pending (analogous to the <i>IP</i> bits for other interrupt types):</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No timer interrupt is pending</td></tr><tr><td>1</td><td>Timer interrupt is pending</td></tr></table> <p>The state of the <i>TI</i> bit is available on the external core interface as the <i>SI_TimerInt</i> signal.</p> | Encoding | Meaning | 0 | No timer interrupt is pending | 1 | Timer interrupt is pending | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No timer interrupt is pending | | | | | | | | | |
| 1 | Timer interrupt is pending | | | | | | | | | |
| CE | 29:28 | Coprocessor unit number referenced when a Coprocessor Unusable exception is taken. This field is loaded by hardware on every exception, but is UNPREDICTABLE for all exceptions except for Coprocessor Unusable. | R | Undefined | | | | | | |
| DC | 27 | <p>Disable <i>Count</i> register. In some power-sensitive applications, the <i>Count</i> register is not used and is the source of meaningful power dissipation. This bit allows the <i>Count</i> register to be stopped in such situations.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Enable counting of <i>Count</i> register</td></tr><tr><td>1</td><td>Disable counting of <i>Count</i> register</td></tr></table> | Encoding | Meaning | 0 | Enable counting of <i>Count</i> register | 1 | Disable counting of <i>Count</i> register | R/W | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | Enable counting of <i>Count</i> register | | | | | | | | | |
| 1 | Disable counting of <i>Count</i> register | | | | | | | | | |
| PCI | 26 | <p>Performance Counter Interrupt: This bit denotes whether a performance counter interrupt is pending (analogous to the <i>IP</i> bits for other interrupt types):</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No performance counter interrupt is pending</td></tr><tr><td>1</td><td>Performance counter interrupt is pending</td></tr></table> <p>The state of the <i>PCI</i> bit is available on the external core interface as the <i>SI_PCInt</i> signal.</p> | Encoding | Meaning | 0 | No performance counter interrupt is pending | 1 | Performance counter interrupt is pending | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No performance counter interrupt is pending | | | | | | | | | |
| 1 | Performance counter interrupt is pending | | | | | | | | | |
| IV | 23 | <p>Indicates whether an interrupt exception uses the general exception vector or a special interrupt vector:</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Use the general exception vector (16#180)</td></tr><tr><td>1</td><td>Use the special interrupt vector (16#200)</td></tr></table> <p>If the <i>Cause_{IV}</i> is 1 and <i>Status_{BEV}</i> is 0, the special interrupt vector represents the base of the vectored interrupt table.</p> | Encoding | Meaning | 0 | Use the general exception vector (16#180) | 1 | Use the special interrupt vector (16#200) | R/W | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Use the general exception vector (16#180) | | | | | | | | | |
| 1 | Use the special interrupt vector (16#200) | | | | | | | | | |

Table 6.23 Cause Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | | |
|----------|-------|---|--------------|-------------|---------|----|-----|------------------------------|----|-----|------------------------------|-----|-----------|----------------------|----|-----|----------------------|----|-----|----------------------|----|-----|----------------------|---|-----------|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | | | | |
| WP | 22 | Indicates that a watch exception was deferred because <i>Status_{EXL}</i> or <i>Status_{ERL}</i> were a one at the time the watch exception was detected. This bit both indicates that the watch exception was deferred, and causes the exception to be initiated once <i>Status_{EXL}</i> and <i>Status_{ERL}</i> are both zero. As such, software must clear this bit as part of the watch exception handler to prevent a watch exception loop. Software should not write a 1 to this bit when its value is a 0, thereby causing a 0-to-1 transition. If such a transition is caused by software, it is UNPREDICTABLE whether hardware ignores the write, accepts the write with no side effects, or accepts the write and initiates a watch exception once <i>Status_{EXL}</i> and <i>Status_{ERL}</i> are both zero. | R/W | Undefined | | | | | | | | | | | | | | | | | | | | | |
| IP7..IP2 | 15:10 | <div>Indicates an interrupt is pending:</div> <table><tr><th>Bit</th><th>Name</th><th>Meaning</th></tr><tr><td>15</td><td>IP7</td><td>Hardware interrupt 5</td></tr><tr><td>14</td><td>IP6</td><td>Hardware interrupt 4</td></tr><tr><td>13</td><td>IP5</td><td>Hardware interrupt 3</td></tr><tr><td>12</td><td>IP4</td><td>Hardware interrupt 2</td></tr><tr><td>11</td><td>IP3</td><td>Hardware interrupt 1</td></tr><tr><td>10</td><td>IP2</td><td>Hardware interrupt 0</td></tr></table> <div>If EIC interrupt mode is not enabled (<i>Config3_{VEIC}</i> = 0), timer interrupts are combined in a system-dependent way with any hardware interrupt. If EIC interrupt mode is enabled (<i>Config3_{VEIC}</i> = 1), these bits take on a different meaning and are interpreted as the <i>RIPL</i> field, described below. See Section 5.3 “Interrupts” for a general description of interrupt processing.</div> | Bit | Name | Meaning | 15 | IP7 | Hardware interrupt 5 | 14 | IP6 | Hardware interrupt 4 | 13 | IP5 | Hardware interrupt 3 | 12 | IP4 | Hardware interrupt 2 | 11 | IP3 | Hardware interrupt 1 | 10 | IP2 | Hardware interrupt 0 | R | Undefined |
| Bit | Name | Meaning | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | IP7 | Hardware interrupt 5 | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | IP6 | Hardware interrupt 4 | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | IP5 | Hardware interrupt 3 | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | IP4 | Hardware interrupt 2 | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | IP3 | Hardware interrupt 1 | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | IP2 | Hardware interrupt 0 | | | | | | | | | | | | | | | | | | | | | | | |
| RIPL | 15:10 | <div>Requested Interrupt Priority Level: If EIC interrupt mode is enabled (<i>Config3_{VEIC}</i> = 1), this field is the encoded (0..63) value of the requested interrupt. A value of zero indicates that no interrupt is requested. If EIC interrupt mode is not enabled (<i>Config3_{VEIC}</i> = 0), these bits take on a different meaning and are interpreted as the <i>IP7..IP2</i> bits, described above.</div> | R | Undefined | | | | | | | | | | | | | | | | | | | | | |
| IP1..IP0 | 9:8 | <div>Controls the request for software interrupts:</div> <table><tr><th>Bit</th><th>Name</th><th>Meaning</th></tr><tr><td>9</td><td>IP1</td><td>Request software interrupt 1</td></tr><tr><td>8</td><td>IP0</td><td>Request software interrupt 0</td></tr></table> <div>These bits are exported to an external interrupt controller for prioritization in EIC interrupt mode with other interrupt sources. The state of these bits is available on the external core interface as the <i>SL_SWInt[1:0]</i> bus.</div> | Bit | Name | Meaning | 9 | IP1 | Request software interrupt 1 | 8 | IP0 | Request software interrupt 0 | R/W | Undefined | | | | | | | | | | | | |
| Bit | Name | Meaning | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | IP1 | Request software interrupt 1 | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | IP0 | Request software interrupt 0 | | | | | | | | | | | | | | | | | | | | | | | |
| ExcCode | 6:2 | Exception code - see Table 6.24 | R | Undefined | | | | | | | | | | | | | | | | | | | | | |

Table 6.23 Cause Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|----------------------------|--|--------------|-------------|
| Name | Bits | | | |
| 0 | 25:24, 21:16, 7, 1:0 | Must be written as zero; returns zero on read. | 0 | 0 |

Table 6.24 Cause Register ExcCode Field

| Exception Code Value | | Mnemonic | Description |
|----------------------|-------------|----------|---|
| Decimal | Hexadecimal | | |
| 0 | 16#00 | Int | Interrupt |
| 1 | 16#01 | Mod | TLB modification exception |
| 2 | 16#02 | TLBL | TLB exception (load or instruction fetch) |
| 3 | 16#03 | TLBS | TLB exception (store) |
| 4 | 16#04 | AdEL | Address error exception (load or instruction fetch) |
| 5 | 16#05 | AdES | Address error exception (store) |
| 6 | 16#06 | IBE | Bus error exception (instruction fetch) |
| 7 | 16#07 | DBE | Bus error exception (data reference: load or store) |
| 8 | 16#08 | Sys | Syscall exception |
| 9 | 16#09 | Bp | Breakpoint exception. If an SDBBP instruction is executed while the processor is running in EJTAG Debug Mode, this value is written to the <i>DebugDExcCode</i> field to denote an SDBBP in Debug Mode. |
| 10 | 16#0a | RI | Reserved instruction exception |
| 11 | 16#0b | CpU | Coprocessor Unusable exception |
| 12 | 16#0c | Ov | Arithmetic Overflow exception |
| 13 | 16#0d | Tr | Trap exception |
| 14 | 16#0e | - | Reserved |
| 15 | 16#0f | FPE | Floating point exception |
| 16 | 16#10 | IS1 | Coprocessor 2 implementation specific exception |
| 17 | 16#11 | CEU | CorExtend Unusable |
| 18 | 16#12 | C2E | Precise Coprocessor 2 exception |
| 19-22 | 16#13-16#16 | - | Reserved |
| 23 | 16#17 | WATCH | Reference to <i>WatchHi/WatchLo</i> address |
| 24 | 16#18 | MCheck | Machine checkcore |
| 25-29 | 16#19-16#1d | - | Reserved |
| 30 | 16#1e | CacheErr | Cache error. In normal mode, a cache error exception has a dedicated vector and the Cause register is not updated. If a cache error occurs while in Debug Mode, this code is written to the <i>DebugDExcCode</i> field to indicate that re-entry to Debug Mode was caused by a cache error. |

Table 6.24 Cause Register ExcCode Field (Continued)

| Exception Code Value | | Mnemonic | Description |
|----------------------|-------------|----------|-------------|
| Decimal | Hexadecimal | | |
| 31 | 16#1f | - | Reserved |

6.2.18 Exception Program Counter (CP0 Register 14, Select 0)

The Exception Program Counter (*EPC*) is a read/write register that contains the address at which processing resumes after an exception has been serviced. All bits of the *EPC* register are significant and must be writable.

For synchronous (precise) exceptions, the *EPC* contains one of the following:

- The virtual address of the instruction that was the direct cause of the exception
- The virtual address of the immediately preceding branch or jump instruction, when the exception causing instruction is in a branch delay slot and the *Branch Delay* bit in the *Cause* register is set.

On new exceptions, the processor does not write to the *EPC* register when the *EXL* bit in the *Status* register is set, however, the register can still be written via the MTC0 instruction.

In processors that implement the MIPS16 ASE, a read of the *EPC* register (via MFC0) returns the following value in the destination GPR:

$$\text{GPR}[\text{rt}] \leftarrow \text{ExceptionPC}_{31..1} \parallel \text{ISAMode}_0$$

That is, the upper 31 bits of the exception PC are combined with the lower bit of the *ISAMode* field of *DEPC7* and written to the GPR.

Similarly, a write to the *EPC* register (via MTC0) takes the value from the GPR and distributes that value to the exception PC and the *ISAMode* field, as follows

$$\begin{aligned} \text{ExceptionPC} &\leftarrow \text{GPR}[\text{rt}]_{31..1} \parallel 0 \\ \text{ISAMode} &\leftarrow 2\#0 \parallel \text{GPR}[\text{rt}]_0 \end{aligned}$$

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the exception PC, and the lower bit of the exception PC is cleared. The upper bit of the *ISAMode* field is cleared and the lower bit is loaded from the lower bit of the GPR.

Figure 6.19 EPC Register Format

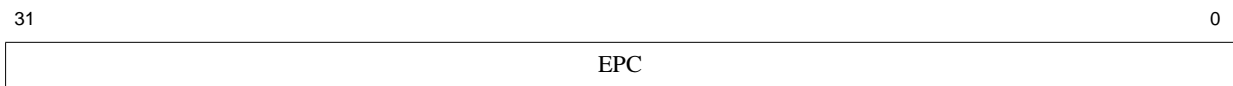


Table 6.25 EPC Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|----------------------------|--------------|-------------|
| Name | Bit(s) | | | |
| EPC | 31:0 | Exception Program Counter. | R/W | Undefined |

6.2.19 Processor Identification (CP0 Register 15, Select 0)

The Processor Identification (*PRId*) register is a 32 bit read-only register that contains information identifying the manufacturer, manufacturer options, processor identification, and revision level of the processor.

Figure 6.20 PRId Register Format

| | | | | | | | |
|---------------|----|------------|----|--------------|---|----------|---|
| 31 | 24 | 23 | 16 | 15 | 8 | 7 | 0 |
| CompanyOption | | Company ID | | Processor ID | | Revision | |

Table 6.26 PRId Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | |
|----------------|----------------|--|--------------|-------------|---------|-----|----------------|--|-----|----------------|---|-----|-------------|---|---|--------|
| Name | Bit(s) | | | | | | | | | | | | | | | |
| Company Option | 31:24 | Implementation specific values | R | Preset | | | | | | | | | | | | |
| Company ID | 23:16 | Identifies the company that designed or manufactured the processor. In the 24K this field contains a value of 1 to indicate MIPS Technologies, Inc. | R | 1 | | | | | | | | | | | | |
| Processor ID | 15:8 | Identifies the type of processor. This field allows software to distinguish between the various types of MIPS Technologies processors. | R | 0x93 | | | | | | | | | | | | |
| Revision | 7:0 | <div>Specifies the revision number of the processor. This field allows software to distinguish between one revision and another of the same processor type. This field is broken up into the following three subfields:</div> <table><tr><th>Bit(s)</th><th>Name</th><th>Meaning</th></tr><tr><td>7:5</td><td>Major Revision</td><td>This number is increased on major revisions of the processor 24k</td></tr><tr><td>4:2</td><td>Minor Revision</td><td>This number is increased on each incremental revision of the processor and reset on each new major revision</td></tr><tr><td>1:0</td><td>Patch Level</td><td>If a patch is made to modify an older revision of the processor, this field will be incremented</td></tr></table> | Bit(s) | Name | Meaning | 7:5 | Major Revision | This number is increased on major revisions of the processor 24k | 4:2 | Minor Revision | This number is increased on each incremental revision of the processor and reset on each new major revision | 1:0 | Patch Level | If a patch is made to modify an older revision of the processor, this field will be incremented | R | Preset |
| Bit(s) | Name | Meaning | | | | | | | | | | | | | | |
| 7:5 | Major Revision | This number is increased on major revisions of the processor 24k | | | | | | | | | | | | | | |
| 4:2 | Minor Revision | This number is increased on each incremental revision of the processor and reset on each new major revision | | | | | | | | | | | | | | |
| 1:0 | Patch Level | If a patch is made to modify an older revision of the processor, this field will be incremented | | | | | | | | | | | | | | |

6.2.20 EBase Register (CP0 Register 15, Select 1)

The *EBase* register is a read/write register containing the base address of the exception vectors used when *StatusBEV* equals 0, and a read-only CPU number value that may be used by software to distinguish different processors in a multi-processor system.

The *EBase* register provides the ability for software to identify the specific processor within a multi-processor system, and allows the exception vectors for each processor to be different, especially in systems composed of heterogeneous processors. Bits 31:12 of the *EBase* register are concatenated with zeros to form the base of the exception vectors when *StatusBEV* is 0. The exception vector base address comes from the fixed defaults (see [Section 5.5 “Exception Vector Locations”](#)) when *StatusBEV* is 1, or for any EJTAG Debug exception. The reset state of bits

31:12 of the *EBase* register initialize the exception base register to 16#8000.0000, providing backward compatibility with Release 1 implementations.

Bits 31:30 of the *EBase* Register are fixed with the value 2#10 to force the exception base address to be in the kseg0 or kseg1 unmapped virtual address segments. Bit 29 of exception base address will be forced to 1 on Cache Error exceptions so the exception handler will be executed from the uncached kseg1 segment.

If the value of the exception base register is to be changed, this must be done with *StatusBEV* equal 1. The operation of the processor is **UNDEFINED** if the Exception Base field is written with a different value when *StatusBEV* is 0.

Combining bits 31:12 with the *Exception Base* field allows the base address of the exception vectors to be placed at any 4KByte page boundary.

Figure 6.21 EBase Register Format

| | | | | | | | | | |
|----|----|----------------|--|----|----|----|---|---|--------|
| 31 | 30 | 29 | | 12 | 11 | 10 | 9 | | 0 |
| 1 | 0 | Exception Base | | | | | | 0 | CPUNum |

Table 6.27 EBase Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|----------------|-----------|---|--------------|----------------|
| Name | Bits | | | |
| 1 | 31 | This bit is ignored on write and returns one on read. | R | 1 |
| Exception Base | 29:12 | In conjunction with bits 31..30, this field specifies the base address of the exception vectors when <i>StatusBEV</i> is zero. | R/W | 0 |
| CPUNum | 9:0 | This field contains an identifier that will be unique among the CPUs in a multi-processor system. This can be used by software to distinguish where it is running. The value in this field is set by the <i>SI_CPUNum[9:0]</i> static input pins to the core. . | R | Externally Set |
| 0 | 30, 11:10 | Must be written as zero; returns zero on read. | 0 | 0 |

6.2.21 Config Register (CP0 Register 16, Select 0)

The *Config* register specifies various configuration and capabilities information. Most of the fields in the *Config* register are initialized by hardware during the Reset exception process, or are constant. The *K0*, *KU*, and *K23* fields must be initialized by software in the Reset exception handler, if the reset value is not desired.

Figure 6.22 Config Register Format — Select 0

| | | | | | | | | | | | | | | | | | | | | | | | | |
|----|-----|----|-----|-----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|---|---|---|---|---|----|
| 31 | 30 | 28 | 27 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 10 | 9 | 7 | 6 | 3 | 2 | 0 |
| M | K23 | KU | ISP | DSP | UDI | SB | 0 | MM | 0 | BM | BE | AT | AR | MT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | K0 |

Table 6.28 Config Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| M | 31 | This bit is hardwired to '1' to indicate the presence of the <i>Config1</i> register. | R | 1 |

Table 6.28 Config Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|---|---|-------------------|---------------------|---|--|---|---|-----|----------------|
| Name | Bit(s) | | | | | | | | | |
| K23 | 30:28 | This field controls the cacheability of the kseg2 and kseg3 address segments in FM implementations. Refer to Table 6.29 for the field encoding. | FM: R/W TLB: R | FM: 010 TLB: 000 | | | | | | |
| KU | 27:25 | This field controls the cacheability of the kuseg and useg address segments in FM implementations. Refer to Table 6.29 for the field encoding. | FM: R/W TLB: R | FM: 010 TLB: 000 | | | | | | |
| ISP | 24 | I-side ScratchPad RAM present | R | Preset | | | | | | |
| DSP | 23 | D-side ScratchPad RAM present | R | Preset | | | | | | |
| UDI | 22 | This bit indicates that CorExtend User Defined Instructions have been implemented. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No User Defined Instructions are implemented</td></tr><tr><td>1</td><td>User Defined Instructions are implemented</td></tr></table> | Encoding | Description | 0 | No User Defined Instructions are implemented | 1 | User Defined Instructions are implemented | R | Preset |
| Encoding | Description | | | | | | | | | |
| 0 | No User Defined Instructions are implemented | | | | | | | | | |
| 1 | User Defined Instructions are implemented | | | | | | | | | |
| SB | 21 | Indicates whether SimpleBE bus mode is enabled. Set via SI_SimpleBE input pin. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No reserved byte enables on OCP interface</td></tr><tr><td>1</td><td>Only simple byte enables allowed on OCP interface</td></tr></table> | Encoding | Description | 0 | No reserved byte enables on OCP interface | 1 | Only simple byte enables allowed on OCP interface | R | Externally Set |
| Encoding | Description | | | | | | | | | |
| 0 | No reserved byte enables on OCP interface | | | | | | | | | |
| 1 | Only simple byte enables allowed on OCP interface | | | | | | | | | |
| MM | 18 | This bit indicates whether write-through merging is enabled in the 32-byte collapsing write buffer. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No Merging</td></tr><tr><td>1</td><td>Merging allowed</td></tr></table> | Encoding | Description | 0 | No Merging | 1 | Merging allowed | R/W | 1 |
| Encoding | Description | | | | | | | | | |
| 0 | No Merging | | | | | | | | | |
| 1 | Merging allowed | | | | | | | | | |
| BM | 16 | Burst order. Set via SI_SBlock input pin. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Sequential</td></tr><tr><td>1</td><td>SubBlock</td></tr></table> | Encoding | Description | 0 | Sequential | 1 | SubBlock | R | Externally Set |
| Encoding | Description | | | | | | | | | |
| 0 | Sequential | | | | | | | | | |
| 1 | SubBlock | | | | | | | | | |
| BE | 15 | Indicates the endian mode in which the processor is running. Set via SI_Endian input pin. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Little endian</td></tr><tr><td>1</td><td>Big endian</td></tr></table> | Encoding | Description | 0 | Little endian | 1 | Big endian | R | Externally Set |
| Encoding | Description | | | | | | | | | |
| 0 | Little endian | | | | | | | | | |
| 1 | Big endian | | | | | | | | | |
| AT | 14:13 | Architecture type implemented by the processor. This field is always 00 to indicate the MIPS32 architecture. | R | 00 | | | | | | |

Table 6.28 Config Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | |
|-----------|----------------|---|--------------|-------------|---|--------------|---|---------------|-----------|----------|---|--------|
| Name | Bit(s) | | | | | | | | | | | |
| AR | 12:10 | Architecture revision level. This field is always 001 to indicate MIPS32 Release 2. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Release 1</td></tr><tr><td>1</td><td>Release 2</td></tr><tr><td>2:7</td><td>Reserved</td></tr></table> | Encoding | Description | 0 | Release 1 | 1 | Release 2 | 2:7 | Reserved | R | 001 |
| Encoding | Description | | | | | | | | | | | |
| 0 | Release 1 | | | | | | | | | | | |
| 1 | Release 2 | | | | | | | | | | | |
| 2:7 | Reserved | | | | | | | | | | | |
| MT | 9:7 | MMU Type: <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>1</td><td>Standard TLB</td></tr><tr><td>3</td><td>Fixed Mapping</td></tr><tr><td>0, 2, 4:7</td><td>Reserved</td></tr></table> | Encoding | Description | 1 | Standard TLB | 3 | Fixed Mapping | 0, 2, 4:7 | Reserved | R | Preset |
| Encoding | Description | | | | | | | | | | | |
| 1 | Standard TLB | | | | | | | | | | | |
| 3 | Fixed Mapping | | | | | | | | | | | |
| 0, 2, 4:7 | Reserved | | | | | | | | | | | |
| K0 | 2:0 | Kseg0 coherency algorithm. Refer to Table 6.29 for the field encoding. | R/W | 010 | | | | | | | | |
| 0 | 20:19, 17, 6:3 | Must be written as zeros; returns zeros on reads. | 0 | 0 | | | | | | | | |

Table 6.29 Cache Coherency Attributes

| K0(2:0) Value | Cache Coherency Attribute |
|---------------|--|
| 0 | Cacheable, noncoherent, write-through, no write allocate |
| 1 | Reserved |
| 2 | Uncached |
| 3 | Cacheable, noncoherent, write-back, write allocate |
| 4,5,6 | Reserved |
| 7 | Uncached Accelerated |

6.2.22 Config1 Register (CP0 Register 16, Select 1)

The *Config1* register is an adjunct to the *Config* register and encodes additional information about capabilities present on the core. All fields in the *Config1* register are read-only.

The instruction and data cache configuration parameters include encodings for the number of sets per way, the line size, and the associativity. The total cache size for a cache is therefore:

$$\text{Associativity} * \text{Line Size} * \text{Sets Per Way}$$

If the line size is zero, no cache is implemented.

Figure 6.23 Config1 Register Format

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----|----------|--|----|----|----|----|----|--|----|----|----|----|----|--|----|----|----|----|----|----|----|---|---|---|---|---|---|---|
| 31 | 30 | | 25 | 24 | | 22 | 21 | | 19 | 18 | | 16 | 15 | | 13 | 12 | | 10 | 9 | | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| M | MMU Size | | IS | | IL | | IA | | DS | | DL | | DA | | C2 | MD | PC | WR | CA | EP | FP | | | | | | | |

Table 6.30 Config1 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | |
|----------|-------------------|--|--------------|-------------|---------|-------------------|---------|------------|---------|------------|---------|------------|---------|----------|---|--------|
| Name | Bit(s) | | | | | | | | | | | | | | | |
| M | 31 | This bit is hardwired to ‘1’ to indicate the presence of the <i>Config2</i> register. | R | 1 | | | | | | | | | | | | |
| MMU Size | 30:25 | This field contains the number of entries in the TLB minus one. The field is read as 0 decimal if the TLB is not implemented | R | Preset | | | | | | | | | | | | |
| IS | 24:22 | <div>This field contains the number of instruction cache sets per way. The corresponding total instruction cache size is shown in parentheses</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0</td><td>64 (8KB)</td></tr><tr><td>0x1</td><td>128 (16KB)</td></tr><tr><td>0x2</td><td>256 (32KB)</td></tr><tr><td>0x3</td><td>512 (64KB)</td></tr><tr><td>0x4:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0 | 64 (8KB) | 0x1 | 128 (16KB) | 0x2 | 256 (32KB) | 0x3 | 512 (64KB) | 0x4:0x7 | Reserved | R | Preset |
| Encoding | Description | | | | | | | | | | | | | | | |
| 0x0 | 64 (8KB) | | | | | | | | | | | | | | | |
| 0x1 | 128 (16KB) | | | | | | | | | | | | | | | |
| 0x2 | 256 (32KB) | | | | | | | | | | | | | | | |
| 0x3 | 512 (64KB) | | | | | | | | | | | | | | | |
| 0x4:0x7 | Reserved | | | | | | | | | | | | | | | |
| IL | 21:19 | <div>This field contains the instruction cache line size The cache line size is fixed at 32 bytes when the I-Cache is present. A value of 0 indicates no ICache.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0</td><td>No ICache present</td></tr><tr><td>0x1:0x3</td><td>Reserved</td></tr><tr><td>0x4</td><td>32 bytes</td></tr><tr><td>0x5:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0 | No ICache present | 0x1:0x3 | Reserved | 0x4 | 32 bytes | 0x5:0x7 | Reserved | R | Preset | | |
| Encoding | Description | | | | | | | | | | | | | | | |
| 0x0 | No ICache present | | | | | | | | | | | | | | | |
| 0x1:0x3 | Reserved | | | | | | | | | | | | | | | |
| 0x4 | 32 bytes | | | | | | | | | | | | | | | |
| 0x5:0x7 | Reserved | | | | | | | | | | | | | | | |
| IA | 18:16 | <div>This field contains the level of instruction cache associativity This field is fixed at 4-way set associative</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0:0x2</td><td>Reserved</td></tr><tr><td>0x3</td><td>4-way</td></tr><tr><td>0x4:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0:0x2 | Reserved | 0x3 | 4-way | 0x4:0x7 | Reserved | R | 0x3 | | | | |
| Encoding | Description | | | | | | | | | | | | | | | |
| 0x0:0x2 | Reserved | | | | | | | | | | | | | | | |
| 0x3 | 4-way | | | | | | | | | | | | | | | |
| 0x4:0x7 | Reserved | | | | | | | | | | | | | | | |
| DS | 15:13 | <div>This field contains the number of data cache sets per way. The corresponding total data cache size is shown in parentheses</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0</td><td>64 (8KB)</td></tr><tr><td>0x1</td><td>128 (16KB)</td></tr><tr><td>0x2</td><td>256 (32KB)</td></tr><tr><td>0x3</td><td>512 (64KB)</td></tr><tr><td>0x4:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0 | 64 (8KB) | 0x1 | 128 (16KB) | 0x2 | 256 (32KB) | 0x3 | 512 (64KB) | 0x4:0x7 | Reserved | R | Preset |
| Encoding | Description | | | | | | | | | | | | | | | |
| 0x0 | 64 (8KB) | | | | | | | | | | | | | | | |
| 0x1 | 128 (16KB) | | | | | | | | | | | | | | | |
| 0x2 | 256 (32KB) | | | | | | | | | | | | | | | |
| 0x3 | 512 (64KB) | | | | | | | | | | | | | | | |
| 0x4:0x7 | Reserved | | | | | | | | | | | | | | | |

Table 6.30 Config1 Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|----------|---|---|--------------|-------------|---------|--------------------------------|---------|---|---------|----------|---------|----------|---|--------|
| Name | Bit(s) | | | | | | | | | | | | | |
| DL | 12:10 | <div>This field contains the data cache line size. The cache line size is fixed at 32 bytes when a D-cache is present. This field reads 0 when a D-cache is not present.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0</td><td>No DCache present</td></tr><tr><td>0x1:0x3</td><td>Reserved</td></tr><tr><td>0x4</td><td>32 bytes</td></tr><tr><td>0x5:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0 | No DCache present | 0x1:0x3 | Reserved | 0x4 | 32 bytes | 0x5:0x7 | Reserved | R | Preset |
| Encoding | Description | | | | | | | | | | | | | |
| 0x0 | No DCache present | | | | | | | | | | | | | |
| 0x1:0x3 | Reserved | | | | | | | | | | | | | |
| 0x4 | 32 bytes | | | | | | | | | | | | | |
| 0x5:0x7 | Reserved | | | | | | | | | | | | | |
| DA | 9:7 | <div>This field contains the type of set associativity for the data cache. The associativity is fixed at 4-way.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0x0:0x2</td><td>Reserved</td></tr><tr><td>0x3</td><td>4-way</td></tr><tr><td>0x4:0x7</td><td>Reserved</td></tr></table> | Encoding | Description | 0x0:0x2 | Reserved | 0x3 | 4-way | 0x4:0x7 | Reserved | R | 0x3 | | |
| Encoding | Description | | | | | | | | | | | | | |
| 0x0:0x2 | Reserved | | | | | | | | | | | | | |
| 0x3 | 4-way | | | | | | | | | | | | | |
| 0x4:0x7 | Reserved | | | | | | | | | | | | | |
| C2 | 6 | <div>Coprocessor 2 present.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Coprocessor2 not present</td></tr><tr><td>1</td><td>Coprocessor2 present</td></tr></table> | Encoding | Description | 0 | Coprocessor2 not present | 1 | Coprocessor2 present | R | Preset | | | | |
| Encoding | Description | | | | | | | | | | | | | |
| 0 | Coprocessor2 not present | | | | | | | | | | | | | |
| 1 | Coprocessor2 present | | | | | | | | | | | | | |
| MD | 5 | MDMX implemented. | R | 0 | | | | | | | | | | |
| PC | 4 | Performance Counter registers implemented. | R | 1 | | | | | | | | | | |
| WR | 3 | <div>Watch registers implemented.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No Watch registers are present</td></tr><tr><td>1</td><td>One or more Watch registers are present</td></tr></table> | Encoding | Description | 0 | No Watch registers are present | 1 | One or more Watch registers are present | R | 1 | | | | |
| Encoding | Description | | | | | | | | | | | | | |
| 0 | No Watch registers are present | | | | | | | | | | | | | |
| 1 | One or more Watch registers are present | | | | | | | | | | | | | |
| CA | 2 | <div>Code compression (MIPS16) implemented.</div> <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No MIPS16 present</td></tr><tr><td>1</td><td>MIPS16 is implemented</td></tr></table> | Encoding | Description | 0 | No MIPS16 present | 1 | MIPS16 is implemented | R | 1 | | | | |
| Encoding | Description | | | | | | | | | | | | | |
| 0 | No MIPS16 present | | | | | | | | | | | | | |
| 1 | MIPS16 is implemented | | | | | | | | | | | | | |
| EP | 1 | EJTAG present: This bit is always set to indicate that the core implements EJTAG. | R | 1 | | | | | | | | | | |
| FP | 0 | FPU implemented. | R | Preset | | | | | | | | | | |

6.2.23 Config2 Register (CP0 Register 16, Select 2)

The *Config2* register is an adjunct to the *Config* register and is reserved to encode additional capabilities information. *Config2* is allocated for showing the configuration of level 2/3 caches. L2 values reflect the configuration information

input from the L2 module. L3 fields are reset to 0 because L3 caches are not supported by the 24K core. All fields in the *Config2* register are read-only.

Figure 6.24 Config2 Register Format

| | | | | | | | | | | | | | | | | | |
|----|----|----|----|----|----|-----|----|----|----|----|----|----|---|---|---|---|---|
| 31 | 30 | 28 | 27 | 24 | 23 | 20 | 19 | 16 | 15 | 13 | 12 | 11 | 8 | 7 | 4 | 3 | 0 |
| M | TU | TS | TL | TA | SU | L2B | SS | SL | SA | | | | | | | | |

Table 6.31 Config2 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | |
|----------|-------------|---|--------------|-------------|---|----|---|-----|---|-----|---|-----|---|------|---|------|---|------|---|------|------|----------|---|--------|
| Name | Bit(s) | | | | | | | | | | | | | | | | | | | | | | | |
| M | 31 | This bit is hardwired to ‘1’ to indicate the presence of the Config3 register. | R | 1 | | | | | | | | | | | | | | | | | | | | |
| TU | 30:28 | Implementation specific tertiary cache control. Tertiary cache not supported | R | 0 | | | | | | | | | | | | | | | | | | | | |
| TS | 27:24 | Tertiary cache sets per way. Tertiary cache not supported | R | 0 | | | | | | | | | | | | | | | | | | | | |
| TL | 23:20 | Tertiary cache line size. Tertiary cache not supported | R | 0 | | | | | | | | | | | | | | | | | | | | |
| TA | 19:16 | Tertiary cache associativity. Tertiary cache not supported | R | 0 | | | | | | | | | | | | | | | | | | | | |
| SU | 15:13 | Reserved | R | 0 | | | | | | | | | | | | | | | | | | | | |
| L2B | 12 | L2 Bypass/L2_Bypassed. In systems which include an L2 cache, writing a 1 to this bit, will set the <i>L2_Bypass</i> output from the core. Setting the <i>L2_Bypass</i> output, directs the L2 cache to go into bypass mode. L2 responds by asserting its <i>L2_Bypassed</i> output pin. The value of <i>L2_Bypassed</i> is returned when L2B is read. Since this involves a communication between CPU and L2, reading this bit will reflect the new value with some implementation- and clock ratio- dependent delay. | R/W | 0 | | | | | | | | | | | | | | | | | | | | |
| SS | 11:8 | Secondary cache sets per way <table border="1"><thead><tr><th>Encoding</th><th>Description</th></tr></thead><tbody><tr><td>0</td><td>64</td></tr><tr><td>1</td><td>128</td></tr><tr><td>2</td><td>256</td></tr><tr><td>3</td><td>512</td></tr><tr><td>4</td><td>1024</td></tr><tr><td>5</td><td>2048</td></tr><tr><td>6</td><td>4096</td></tr><tr><td>7</td><td>8192</td></tr><tr><td>8-15</td><td>Reserved</td></tr></tbody></table> | Encoding | Description | 0 | 64 | 1 | 128 | 2 | 256 | 3 | 512 | 4 | 1024 | 5 | 2048 | 6 | 4096 | 7 | 8192 | 8-15 | Reserved | R | Preset |
| Encoding | Description | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 64 | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 128 | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 256 | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 512 | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | 1024 | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | 2048 | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 4096 | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 8192 | | | | | | | | | | | | | | | | | | | | | | | |
| 8-15 | Reserved | | | | | | | | | | | | | | | | | | | | | | | |

Figure 6.25 Config3 Register Format

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| M | 31 | This bit is reserved to indicate if a <i>Config4</i> register is present. | R | 0 |
| ULRI | 13 | User Local Register Implemented: Indicates that the Cop0 <i>UserLocal</i> register is present. | R | 1 |

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Table 6.32 Config3 Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|---|---|--------------|-------------|---|---|---|---|---|----------------|
| Name | Bits | | | | | | | | | |
| DSPP | 10 | DSP Present. Indicates whether support for the DSP ASE is implemented. On the 24K core, this bit is always 0, because the DSP ASE is not implemented. | R | 0 | | | | | | |
| VEIC | 6 | Support for an external interrupt controller is implemented. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Support for EIC interrupt mode is not implemented</td></tr><tr><td>1</td><td>Support for EIC interrupt mode is implemented</td></tr></table> The value of this bit is set by the static input, <i>SI_EICPresent</i> . This allows external logic to communicate whether an external interrupt controller is attached to the processor or not. | Encoding | Description | 0 | Support for EIC interrupt mode is not implemented | 1 | Support for EIC interrupt mode is implemented | R | Externally Set |
| Encoding | Description | | | | | | | | | |
| 0 | Support for EIC interrupt mode is not implemented | | | | | | | | | |
| 1 | Support for EIC interrupt mode is implemented | | | | | | | | | |
| VInt | 5 | Vectored interrupts implemented. This bit indicates whether vectored interrupts are implemented. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Vector interrupts are not implemented</td></tr><tr><td>1</td><td>Vectored interrupts are implemented</td></tr></table> On the 24K core, this bit is always a 1 since vectored interrupts are implemented. | Encoding | Description | 0 | Vector interrupts are not implemented | 1 | Vectored interrupts are implemented | R | 1 |
| Encoding | Description | | | | | | | | | |
| 0 | Vector interrupts are not implemented | | | | | | | | | |
| 1 | Vectored interrupts are implemented | | | | | | | | | |
| SP | 4 | Small (1KByte) page support is implemented, and the <i>PageGrain</i> register exists. This bit will always be 0 since small pages are not supported. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Small page support is not implemented</td></tr><tr><td>1</td><td>Small page support is implemented</td></tr></table> | Encoding | Description | 0 | Small page support is not implemented | 1 | Small page support is implemented | R | 0 |
| Encoding | Description | | | | | | | | | |
| 0 | Small page support is not implemented | | | | | | | | | |
| 1 | Small page support is implemented | | | | | | | | | |
| MT | 2 | This bit indicates if the MIPS MT (multi-threading) ASE implemented. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>MIPS MT ASE is not implemented</td></tr><tr><td>1</td><td>MIPS MT ASE is implemented</td></tr></table> | Encoding | Description | 0 | MIPS MT ASE is not implemented | 1 | MIPS MT ASE is implemented | R | 0 |
| Encoding | Description | | | | | | | | | |
| 0 | MIPS MT ASE is not implemented | | | | | | | | | |
| 1 | MIPS MT ASE is implemented | | | | | | | | | |
| SM | 1 | This bit indicates whether the SmartMIPS™ ASE is implemented. Since SmartMIPS is not present on the 24K core, this bit will always be 0. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>SmartMIPS ASE is not implemented</td></tr><tr><td>1</td><td>SmartMIPS ASE is implemented</td></tr></table> | Encoding | Description | 0 | SmartMIPS ASE is not implemented | 1 | SmartMIPS ASE is implemented | R | 0 |
| Encoding | Description | | | | | | | | | |
| 0 | SmartMIPS ASE is not implemented | | | | | | | | | |
| 1 | SmartMIPS ASE is implemented | | | | | | | | | |

Table 6.32 Config3 Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|--------------------------------|---|--------------|-------------|---|--------------------------------|---|----------------------------|---|--------|
| Name | Bits | | | | | | | | | |
| TL | 0 | Trace Logic implemented. This bit indicates whether MIPS trace support is implemented. <div><table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Trace logic is not implemented</td></tr><tr><td>1</td><td>Trace logic is implemented</td></tr></table></div> | Encoding | Description | 0 | Trace logic is not implemented | 1 | Trace logic is implemented | R | Preset |
| Encoding | Description | | | | | | | | | |
| 0 | Trace logic is not implemented | | | | | | | | | |
| 1 | Trace logic is implemented | | | | | | | | | |
| 0 | 30:11, 9:7, 3 | Must be written as zeros; returns zeros on read | 0 | 0 | | | | | | |

6.2.25 Config7 Register (CP0 Register 16, Select 7)

The *Config7* register contains implementation specific configuration information. A number of these bits are writeable to disable certain performance enhancing features within the core.

Figure 6.26 Config7 Register Format

| | | | | | | | | | | | | | | | | | | | | | | | |
|-----|----|--|---|-----|-----|----|----|----|--|-----|-----|----|---|--|-------|-------|-----|----|-----|-----|----|---|---|
| 31 | 30 | | | 19 | 18 | 17 | 16 | 15 | | 10 | 9 | 8 | 7 | | 6 | | 5 | | 4 | 3 | 2 | 1 | 0 |
| WII | 0 | | 0 | HCI | FPR | AR | | 0 | | IAR | IVA | ES | 0 | | CPOOO | NBLSU | ULB | BP | RPS | BHT | SL | | |

Table 6.33 Config7 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|---|--|--------------|---------------------|---|---|---|--|---|---------------------|
| Name | Bits | | | | | | | | | |
| WII | 31 | Wait IE Ignore: Indicates that this processor will allow an interrupt to unblock a WAIT instruction even if <i>IE</i> is preventing the interrupt from being taken. This avoids problems using the WAIT instruction for ‘bottom half’ interrupt servicing. | R | 1 | | | | | | |
| 0 | 30:19, 15:11, 7 | These bits are unused and should be written as 0. | R | 0 | | | | | | |
| HCI | 18 | Hardware Cache Initialization: Indicates that a cache does not require initialization by software. This bit will most likely only be set on simulation-only cache models and not on real hardware. | R | Based on HW present | | | | | | |
| FPR | 17 | Floating Point Ratio: Indicates clock ratio between integer core and floating point unit on 24Kf cores. Reads as 0 on 24Kc cores. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>FP clock frequency is the same as the integer clock</td></tr><tr><td>1</td><td>FP clock frequency is one-half the integer clock</td></tr></table> | Encoding | Description | 0 | FP clock frequency is the same as the integer clock | 1 | FP clock frequency is one-half the integer clock | R | Based on HW present |
| Encoding | Description | | | | | | | | | |
| 0 | FP clock frequency is the same as the integer clock | | | | | | | | | |
| 1 | FP clock frequency is one-half the integer clock | | | | | | | | | |
| AR | 16 | Alias removed: This bit indicates that the data cache is organized to avoid virtual aliasing problems. This bit is only set if the data cache config and MMU type would normally cause aliasing - i.e., only for the 32KB and larger data cache and TLB-based MMU. | R | Based on HW present | | | | | | |

Table 6.33 Config7 Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|---------------------|
| Name | Bits | | | |
| IAR | 10 | Instruction Alias Removed: Indicates that this processor has hardware support to remove instruction cache alias. This hardware is only present when the core is configured with a TLB and cache sizes 32KB and larger. The hardware is disabled via the <i>I/A</i> bit. | R | Based on HW present |
| IVA | 9 | Instruction Virtual Aliasing fix disable: Setting this bit will disable the HW alias removal on the I-Cache. If this bit is cleared, CACHE Hit Invalidate and SYNCI instructions will look up all possible aliased locations and invalidate the given cache line in all of them. This bit is Read-only if <i>IAR</i> =0 | R/W or R | 0 |
| ES | 8 | Externalize Sync: If this bit is set, and if the downstream device is capable of accepting SYNC's (indicated via the pin <i>SI_SyncTxEn</i>), the SYNC instruction will cause a SYNC specific transaction to go out on the external bus. If this bit is cleared or if <i>SI_SyncTxEn</i> is deasserted, no transaction will go out, but all SYNC handling internal to the core will still be performed. When this bit is read, the value returned depends on the state of the <i>SI_SyncTxEn</i> pin. If <i>SI_SyncTxEn</i> is 0, a value of 0 is returned. If <i>SI_SyncTxEn</i> is 1, the value returned is the last value that was written to this bit. Refer to SYNC instruction description for more information. | R/W | 0 |
| CPOOO | 6 | Out-of-order data return on the Coprocessor interfaces: Writing 1 to this bit disables the out-of-order data return for the FPU and COP2. | R/W | 0 |
| NBLSU | 5 | Non-Blocking LSU: Writing 1 to this field will lock the LSU and ALU pipelines together. This forces LSU pipeline stalls to also stall the ALU pipeline. | R/W | 0 |
| ULB | 4 | Uncached Loads Blocking: Writing 1 to this field will make all uncached loads blocking. | R/W | 0 |
| BP | 3 | Branch Prediction: Writing 1 to this field will disable all speculative branch prediction. The fetch unit will wait for a branch to be resolved before fetching the target or fall-through path. | R/W | 0 |
| RPS | 2 | Return Prediction Stack: Writing 1 to this field will disable the use of the Return Prediction Stack. Returns (JR ra) will stall instruction fetch until the destination is calculated. | R/W | 0 |
| BHT | 1 | Branch History Table: Writing 1 to this field will disable the dynamic branch prediction. Branches will be statically predicted taken. | R/W | 0 |
| SL | 0 | Scheduled Loads: Writing 1 to this field will make load misses blocking. | R/W | 0 |

External interventions are also checked against the LLAddr registers.

6.2.26 WatchLo Register (CP0 Register 18, Select 0-3)

The *WatchLo* and *WatchHi* registers together provide the interface to a watchpoint debug facility that initiates a watch exception if an instruction or data access matches the address specified in the registers. As such, they duplicate some functions of the EJTAG debug solution. Watch exceptions are taken only if the *EXL* and *ERL* bits are both zero in the

Status register. If either bit is a one, the *WP* bit is set in the *Cause* register, and the watch exception is deferred until both the *EXL* and *ERL* bits are zero.

There are 4 sets of Watch register pairs (*WatchLo*, *WatchHi*). Two of them (select 0, 1) are associated with instruction addresses only. Thus, only the *I* bit is writeable, and the *R* and *W* bits are tied to 0. The other two (select 2, 3) are associated with data addresses and can only be used for R or W watchpoints.

The *WatchLo* register specifies the base virtual address and the type of reference (instruction fetch, load, store) to match.

Figure 6.27 WatchLo Register Format

| | | | | |
|-------|---|---|---|---|
| | 3 | 2 | 1 | 0 |
| VAddr | I | R | W | |

Table 6.34 WatchLo Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| VAddr | 31:3 | This field specifies the virtual address to match. Note that this is a doubleword address, since bits [2:0] are used to control the type of match. | R/W | Undefined |
| I | 2 | If this bit is set, watch exceptions are enabled for instruction fetches that match the address. | R/W | 0 |
| R | 1 | If this bit is set, watch exceptions are enabled for loads that match the address. | R/W | 0 |
| W | 0 | If this bit is set, watch exceptions are enabled for stores that match the address. | R/W | 0 |

6.2.27 WatchHi Register (CP0 Register 19, Select 0-3)

The *WatchLo* and *WatchHi* registers together provide the interface to a watchpoint debug facility that initiates a watch exception if an instruction or data access matches the address specified in the registers. As such, they duplicate some functions of the EJTAG debug solution. Watch exceptions are taken only if the *EXL* and *ERL* bits are zero in the *Status* register. If either bit is a one, then the *WP* bit is set in the *Cause* register, and the watch exception is deferred until both the *EXL* and *ERL* bits are zero.

The *WatchHi* register contains information that qualifies the virtual address specified in the *WatchLo* register: an *ASID*, a *Global (G)* bit, and an optional address mask. If the *G* bit is 1, then any virtual address reference that matches the specified address will cause a watch exception. If the *G* bit is a 0, only those virtual address references for which the *ASID* value in the *WatchHi* register matches the *ASID* value in the *EntryHi* register cause a watch exception. The optional mask field provides address masking to qualify the address specified in *WatchLo*.

There are 4 sets of Watch register pairs (*WatchLo*, *WatchHi*). Two of them (select 0, 1) are associated with instruction addresses only. Thus, only the *I* bit is meaningful, and the *R* and *W* bits are tied to 0. The other two (select 2, 3) are associated with data addresses and can only be used for R or W watchpoints.

Figure 6.28 WatchHi Register Format

| | | | | | | | | | | | | |
|----------|---|---|-------|--|-------|---|-------|--|-----|---|---|---|
| 31 30 29 | | | 24 23 | | 16 15 | | 12 11 | | 3 2 | | | 0 |
| M | G | 0 | ASID | | | 0 | Mask | | | I | R | W |

Table 6.35 WatchHi Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|-----------------|--|--------------|-------------|
| Name | Bit(s) | | | |
| M | 31 | Indicates the presence of additional Watch registers. | R | Preset |
| G | 30 | If this bit is one, any address that matches that specified in the <i>WatchLo</i> register causes a watch exception. If this bit is zero, the <i>ASID</i> field of the <i>WatchHi</i> register must match the <i>ASID</i> field of the <i>EntryHi</i> register to cause a watch exception. | R/W | Undefined |
| ASID | 23:16 | <i>ASID</i> value which is required to match that in the <i>EntryHi</i> register if the <i>G</i> bit is zero in the <i>WatchHi</i> register. | R/W | Undefined |
| Mask | 11:3 | Bit mask that qualifies the address in the <i>WatchLo</i> register. Any bit in this field that is a set inhibits the corresponding address bit from participating in the address match. | R/W | Undefined |
| I | 2 | This bit is set by hardware when an instruction fetch condition matches the values in this watch register pair. When set, the bit remains set until cleared by software, which is accomplished by writing a 1 to the bit. | W1C | Undefined |
| R | 1 | This bit is set by hardware when a load condition matches the values in this watch register pair. When set, the bit remains set until cleared by software, which is accomplished by writing a 1 to the bit. | W1C | Undefined |
| W | 0 | This bit is set by hardware when a store condition matches the values in this watch register pair. When set, the bit remains set until cleared by software, which is accomplished by writing a 1 to the bit. | W1C | Undefined |
| 0 | 29:24, 15:12 | Must be written as zero; returns zero on read. | 0 | 0 |

6.2.28 Debug Register (CP0 Register 23, Select 0)

The *Debug* register is used to control the debug exception and provide information about the cause of the debug exception and when re-entering at the debug exception vector due to a normal exception in debug mode. The read only information bits are updated every time the debug exception is taken or when a normal exception is taken when already in debug mode.

Only the *DM* bit and the *EJTAGver* field are valid when read from non-debug mode; the values of all other bits and fields are **UNPREDICTABLE**. Operation of the processor is **UNDEFINED** if the *Debug* register is written from non-debug mode.

Some of the bits and fields are only updated on debug exceptions and/or exceptions in debug mode, as shown below:

- *DSS*, *DBp*, *DDBL*, *DDBS*, *DIB*, *DINT* are updated on both debug exceptions and on exceptions in debug modes
- *DExcCode* is updated on exceptions in debug mode, and is undefined after a debug exception
- *Halt* and *Doze* are updated on a debug exception, and are undefined after an exception in debug mode
- *DBD* is updated on both debug and on exceptions in debug modes

All bits and fields are undefined when read from normal mode, except those explicitly described to be defined, e.g. *EJTAGver* and *DM*.

Figure 6.29 Debug Register Format

| | | | | | | | | | | | | | | |
|----------|----------|----------|------|-------|------|---------|--------|---------|---------|--------|------|----------|-----|-----|
| 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | | |
| DBD | DM | NoDCR | LSNM | Doze | Halt | CountDM | IBusEP | MCheckP | CacheEP | DBusEP | IEXI | DDBSImpr | | |
| 18 | 17 | 15 | 14 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| DDBLImpr | EJTAGver | DExcCode | | NoSSt | SSt | R | | R | DINT | DIB | DDBS | DDBL | DBp | DSS |

Table 6.36 Debug Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | |
|--------|--------|---|--------------|-------------|---|
| Name | Bit(s) | | | | |
| DBD | 31 | Indicates whether the last debug exception or exception in debug mode, occurred in a branch delay slot: | R | Undefined | |
| | | Encoding | | | Description |
| | | 0 | | | Not in delay slot |
| | | 1 | | | In delay slot |
| DM | 30 | Indicates that the processor is operating in debug mode: | R | 0 | |
| | | Encoding | | | Description |
| | | 0 | | | Processor is operating in non-debug mode |
| | | 1 | | | Processor is operating in debug mode |
| NoDCR | 29 | Indicates whether the dseg memory segment is present: | R | 0 | |
| | | Encoding | | | Description |
| | | 0 | | | dseg is present |
| | | 1 | | | No dseg present |
| LSNM | 28 | Controls access of load/store between dseg and main memory: | R/W | 0 | |
| | | Encoding | | | Description |
| | | 0 | | | Load/stores in dseg address range goes to dseg |
| | | 1 | | | Load/stores in dseg address range goes to main memory |
| Doze | 27 | Indicates that the processor was in any kind of low power mode when a debug exception occurred: | R | Undefined | |
| | | Encoding | | | Description |
| | | 0 | | | Processor not in low power mode when debug exception occurred |
| | | 1 | | | Processor in low power mode when debug exception occurred |
| Halt | 26 | Indicates that the internal system bus clock was stopped when the debug exception occurred: | R | Undefined | |
| | | Encoding | | | Description |
| | | 0 | | | Internal system bus clock running |
| | | 1 | | | Internal system bus clock stopped |

Table 6.36 Debug Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|---|---|--------------|-------------|--------------------------------------|-------------|---|--------------------------------------|---|---|
| Name | Bit(s) | | | | | | | | | |
| CountDM | 25 | Indicates the Count register behavior in debug mode. | R/W | 1 | | | | | | |
| | | <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Count register stopped in debug mode</td></tr><tr><td>1</td><td>Count register is running in debug mode</td></tr></table> | | | Encoding | Description | 0 | Count register stopped in debug mode | 1 | Count register is running in debug mode |
| | | Encoding | | | Description | | | | | |
| | | 0 | | | Count register stopped in debug mode | | | | | |
| 1 | Count register is running in debug mode | | | | | | | | | |
| IBusEP | 24 | Imprecise instruction fetch Bus Error exception Pending: All instruction bus errors are precise on the 24K core so this bit will always read as 0. Set when an instruction fetch bus error event occurs or if a 1 is written to the bit by software. Cleared when a Bus Error exception on instruction fetch is taken by the processor, and by reset. If <i>IBusEP</i> is set when <i>IEXI</i> is cleared, a Bus Error exception on instruction fetch is taken by the processor, and <i>IBusEP</i> is cleared. | R | 0 | | | | | | |
| MCheckP | 23 | Indicates that an imprecise Machine Check exception is pending. Machine check exceptions are precise on 24K core, so this bit is read only and tied to 0. | R | 0 | | | | | | |
| CacheEP | 22 | Indicates that an imprecise Cache Error is pending. | R/W1 | 0 | | | | | | |
| DBusEP | 21 | Data access Bus Error exception Pending: Set when a data bus error event occurs or if a 1 is written to the bit by software. Cleared when a Data Bus Error exception is taken by the processor, and by reset. If <i>DBusEP</i> is set when <i>IEXI</i> is cleared, a Data Bus Error exception is taken by the processor, and <i>DBusEP</i> is cleared. | R/W1 | 0 | | | | | | |
| IEXI | 20 | Imprecise Error eXception Inhibit: Controls exceptions taken due to imprecise error indications. Set when the processor takes a debug exception or exception in debug mode. Cleared by execution of the DERET instruction; otherwise modifiable by debug mode software. When <i>IEXI</i> is set, the imprecise error exception from a bus error on an instruction fetch or data access, cache error, or machine check is inhibited and deferred until the bit is cleared. | R/W | 0 | | | | | | |
| DDBSImpr | 19 | Indicates that an imprecise Debug Data Break Store exception was taken. | R | 0 | | | | | | |
| DDBLImpr | 18 | Indicates that an imprecise Debug Data Break Load exception was taken. | R | 0 | | | | | | |
| EJTAGver | 17:15 | EJTAG version. | R | 011 | | | | | | |
| | | <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>3</td><td>Version 3.x</td></tr></table> | | | Encoding | Description | 3 | Version 3.x | | |
| | | Encoding | | | Description | | | | | |
| 3 | Version 3.x | | | | | | | | | |
| | | | | | | | | | | |
| DExcCode | 14:10 | Indicates the cause of the latest exception in debug mode. See Table 6.24 for a list of values. Value is undefined after a debug exception. | R | Undefined | | | | | | |
| NoSST | 9 | Indicates whether the single-step feature controllable by the <i>SSt</i> bit is available in this implementation: | R | 0 | | | | | | |
| | | <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>Single-step feature available</td></tr><tr><td>1</td><td>No single-step feature available</td></tr></table> | | | Encoding | Description | 0 | Single-step feature available | 1 | No single-step feature available |
| | | Encoding | | | Description | | | | | |
| | | 0 | | | Single-step feature available | | | | | |
| 1 | No single-step feature available | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

Table 6.36 Debug Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|--|--|--------------|-------------|---|--|---|--|-----|-----------|
| Name | Bit(s) | | | | | | | | | |
| SSt | 8 | Controls if debug single step exception is enabled: <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug single-step exception enabled</td></tr><tr><td>1</td><td>Debug single step exception enabled</td></tr></table> | Encoding | Description | 0 | No debug single-step exception enabled | 1 | Debug single step exception enabled | R/W | 0 |
| Encoding | Description | | | | | | | | | |
| 0 | No debug single-step exception enabled | | | | | | | | | |
| 1 | Debug single step exception enabled | | | | | | | | | |
| R | 7 | Reserved. Must be written as zeros; returns zeros on reads. | R | 0 | | | | | | |
| R | 6 | Reserved. Must be written as zeros; returns zeros on reads. | R | 0 | | | | | | |
| DINT | 5 | Indicates that a debug interrupt exception occurred. Cleared on exception in debug mode. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug interrupt exception</td></tr><tr><td>1</td><td>Debug interrupt exception</td></tr></table> | Encoding | Description | 0 | No debug interrupt exception | 1 | Debug interrupt exception | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug interrupt exception | | | | | | | | | |
| 1 | Debug interrupt exception | | | | | | | | | |
| DIB | 4 | Indicates that a debug instruction break exception occurred. Cleared on exception in debug mode. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug interrupt exception</td></tr><tr><td>1</td><td>Debug interrupt exception</td></tr></table> | Encoding | Description | 0 | No debug interrupt exception | 1 | Debug interrupt exception | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug interrupt exception | | | | | | | | | |
| 1 | Debug interrupt exception | | | | | | | | | |
| DDBS | 3 | Indicates that a debug data break exception occurred on a store. Cleared on exception in debug mode. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug data exception on a store</td></tr><tr><td>1</td><td>Debug instruction exception on a store</td></tr></table> | Encoding | Description | 0 | No debug data exception on a store | 1 | Debug instruction exception on a store | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug data exception on a store | | | | | | | | | |
| 1 | Debug instruction exception on a store | | | | | | | | | |
| DDBL | 2 | Indicates that a debug data break exception occurred on a load. Cleared on exception in debug mode. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug data exception on a load</td></tr><tr><td>1</td><td>Debug instruction exception on a load</td></tr></table> | Encoding | Description | 0 | No debug data exception on a load | 1 | Debug instruction exception on a load | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug data exception on a load | | | | | | | | | |
| 1 | Debug instruction exception on a load | | | | | | | | | |
| DBp | 1 | Indicates that a debug software breakpoint exception occurred. Cleared on exception in debug mode. <table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug software breakpoint exception</td></tr><tr><td>1</td><td>Debug software breakpoint exception</td></tr></table> | Encoding | Description | 0 | No debug software breakpoint exception | 1 | Debug software breakpoint exception | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug software breakpoint exception | | | | | | | | | |
| 1 | Debug software breakpoint exception | | | | | | | | | |

Table 6.36 Debug Register Field Descriptions (Continued)

| Fields | | | Read / Write | Reset State | | | | | | |
|----------|--------------------------------|--|--------------|-------------|---|--------------------------------|---|-----------------------------|---|-----------|
| Name | Bit(s) | | | | | | | | | |
| DSS | 0 | Indicates that a debug single-step exception occurred. Cleared on exception in debug mode. <div><table><tr><th>Encoding</th><th>Description</th></tr><tr><td>0</td><td>No debug single-step exception</td></tr><tr><td>1</td><td>Debug single-step exception</td></tr></table></div> | Encoding | Description | 0 | No debug single-step exception | 1 | Debug single-step exception | R | Undefined |
| Encoding | Description | | | | | | | | | |
| 0 | No debug single-step exception | | | | | | | | | |
| 1 | Debug single-step exception | | | | | | | | | |

6.2.29 Trace Control Register (CP0 Register 23, Select 1)

The *TraceControl* register configuration is shown below.

Figure 6.30 TraceControl Register Format

| | | | | | | | | | | | | | | | | | | | | |
|----|----|----|----|----|----|----|----|----|----|--------|----|----|------|---|---|---|------|------|-----|----|
| 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 13 | 12 | 5 | 4 | 3 | 2 | 1 | 0 | |
| TS | UT | 0 | TB | IO | D | E | K | S | U | ASID_M | | | ASID | | | G | TFCR | TLSM | TIM | On |

Table 6.37 TraceControl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|-------|---|--------------|-------------|
| Name | Bits | | | |
| TS | 31 | The trace select bit is used to select between the hardware and the software trace control bits. A value of zero selects the external hardware trace block signals, and a value of one selects the trace control bits in the <i>TraceControl</i> register. | R/W | 0 |
| UT | 30 | This bit is used to indicate the type of user-triggered trace record. A value of zero implies a user type 1 and a value of one implies a user type 2. The actual triggering of a user trace record happens on a write to the <i>UserTraceData</i> register. This is a 32-bit register for 32-bit processors and a 64-bit register for 64-bit processors. | R/W | Undefined |
| 0 | 29:28 | Reserved for future use; Must be written as zero; returns zero on read. | 0 | 0 |
| TB | 27 | Trace All Branch. When set to 1, this tells the processor to trace the PC value for all taken branches, not just the ones whose branch target address is statically unpredictable. | R/W | Undefined |
| IO | 26 | Inhibit Overflow. This signal is used to indicate to the core trace logic that slow but complete tracing is desired. Hence, the core tracing logic must not allow a FIFO overflow and discard trace data. This is achieved by stalling the pipeline when the FIFO is nearly full, so that no trace records are ever lost. | R/W | Undefined |

Table 6.37 TraceControl Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|-------|--|--------------|-------------|
| Name | Bits | | | |
| D | 25 | When set to one, this enables tracing in Debug Mode. For trace to be enabled in Debug mode, the On bit must be one, and either the G bit must be one, or the current process ASID must match the ASID field in this register. When set to zero, trace is disabled in Debug Mode, irrespective of other bits. | R/W | Undefined |
| E | 24 | When set to one, this enables tracing in Exception Mode. For trace to be enabled in Exception mode, the On bit must be one, and either the G bit must be one, or the current process ASID must match the ASID field in this register. When set to zero, trace is disabled in Exception Mode, irrespective of other bits. | R/W | Undefined |
| K | 23 | When set to one, this enables tracing in Kernel Mode. For trace to be enabled in Kernel mode, the On bit must be one, and either the G bit must be one, or the current process ASID must match the ASID field in this register. When set to zero, trace is disabled in Kernel Mode, irrespective of other bits. | R/W | Undefined |
| S | 22 | When set to one, this enables tracing in Supervisor Mode. For trace to be enabled in Supervisor mode, the On bit must be one, and either the G bit must be one, or the current process ASID must match the ASID field in this register. When set to zero, trace is disabled in Supervisor Mode, irrespective of other bits. If the processor does not implement Supervisor Mode, this bit is ignored on write and returns zero on read. | R/W | Undefined |
| U | 21 | When set to one, this enables tracing in User Mode. For trace to be enabled in User mode, the On bit must be one, and either the G bit must be one, or the current process ASID must match the ASID field in this register. When set to zero, trace is disabled in User Mode, irrespective of other bits. | R/W | Undefined |
| ASID_M | 20:13 | This is a mask value applied to the ASID comparison (done when the G bit is zero). A “1” in any bit in this field inhibits the corresponding ASID bit from participating in the match. As such, a value of zero in this field compares all bits of ASID. Note that the ability to mask the ASID value is not available in the hardware signal bit; it is only available via the software control register. If the processor does not implement the standard TLB-based MMU, this field is ignored on write and returns zero on read. | R/W | Undefined |
| ASID | 12:5 | The ASID field to match when the G bit is zero. When the G bit is one, this field is ignored. If the processor does not implement the standard TLB-based MMU, this field is ignored on write and returns zero on read. | R/W | Undefined |
| G | 4 | When set, this implies that tracing is to be enabled for all processes, provided that other enabling functions (like U, S, etc.) are also true. If the processor does not implement the standard TLB-based MMU, this field is ignored on write and returns 1 on read. This causes all match equations to work correctly in the absence of an ASID. | R/W | Undefined |

Table 6.37 TraceControl Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| TFCR | 3 | When asserted, used to trace function call and return instructions with full PC values. | R/W | Undefined |
| TLSM | 2 | When asserted, used to trace data cache load and store misses with full PC values, and potentially the data address and value as well. | R/W | Undefined |
| TIM | 1 | When asserted, used to trace instruction miss with full PC values. | R/W | Undefined |
| On | 0 | This is the master trace enable switch in software control. When zero, tracing is always disabled. When set to one, tracing is enabled whenever the other enabling functions are also true. | R/W | 0 |

6.2.30 Trace Control2 Register (CP0 Register 23, Select 2)

The *TraceControl2* register provides additional control and status information. Note that some fields in the *TraceControl2* register are read-only, but have a reset state of “Undefined”. This is because these values are loaded from the Trace Control Block (TCB) (see [Section 11.9 “Trace Control Block \(TCB\) Registers \(Hardware Control\)”](#)). As such, these fields in the *TraceControl2* register will not have valid values until the TCB asserts these values.

This register is only implemented if the MIPS Trace capability is present.

Figure 6.31 TraceControl2 Register Format

| | | | | | | | | | | | | | | |
|----|--------|-------|----|----|-----|-------|----|------|---|------------|-----|-----|-----|---|
| 31 | 30 | 29 | 28 | 21 | 20 | 19 | 12 | 11 | 7 | 6 | 5 | 4 | 3 | 2 |
| 0 | CPUIdV | CPUId | | | TCV | TCNum | | Mode | | ValidModes | TBI | TBU | SyP | |

Table 6.38 TraceControl2 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|------------------------------------|-------|---|--------------|-------------|
| Name | Bits | | | |
| 0 | 31:30 | Reserved for future use; Must be written as zero; returns zero on read. | 0 | 0 |
| CPUIdV, CPUId, TCV, TCNum | 29:12 | Used on processors implementing the MT ASE | R | 0 |

Table 6.38 TraceControl2 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | |
|-------------|--|---|--------------|---------------------|----|--|----|--|----|---|----|-----------|----|------------|-----|-----------|
| Name | Bits | | | | | | | | | | | | | | | |
| Mode | 11:7 | <p>These 5 bits provide the same trace mode functions as the <i>PDI_TraceMode[4:0]</i> signal, and is described here again. When tracing is turned on, this signal specifies what information is to be traced by the core. It uses 5 bits, where each bit turns on tracing of a specific tracing mode when that bit value is a 1. If the corresponding bit is 0, then the Trace Value shown in column two is not traced by the processor.</p> <p>On the 24K core, PC tracing is always enabled, regardless of the value on bit 7. The table shows what trace value is turned on:</p> <table><tr><th>Bit</th><th>Trace the Following</th></tr><tr><td>7</td><td>PC</td></tr><tr><td>8</td><td>Load address</td></tr><tr><td>9</td><td>Store address</td></tr><tr><td>10</td><td>Load data</td></tr><tr><td>11</td><td>Store data</td></tr></table> | Bit | Trace the Following | 7 | PC | 8 | Load address | 9 | Store address | 10 | Load data | 11 | Store data | R/W | Undefined |
| Bit | Trace the Following | | | | | | | | | | | | | | | |
| 7 | PC | | | | | | | | | | | | | | | |
| 8 | Load address | | | | | | | | | | | | | | | |
| 9 | Store address | | | | | | | | | | | | | | | |
| 10 | Load data | | | | | | | | | | | | | | | |
| 11 | Store data | | | | | | | | | | | | | | | |
| Valid-Modes | 6:5 | <p>This field specifies the subset of tracing that is supported by the processor.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>00</td><td>PC tracing only</td></tr><tr><td>01</td><td>PC and load and store address tracing only</td></tr><tr><td>10</td><td>PC, load and store address, and load and store data</td></tr><tr><td>11</td><td>Reserved</td></tr></table> | Encoding | Meaning | 00 | PC tracing only | 01 | PC and load and store address tracing only | 10 | PC, load and store address, and load and store data | 11 | Reserved | R | Preset | | |
| Encoding | Meaning | | | | | | | | | | | | | | | |
| 00 | PC tracing only | | | | | | | | | | | | | | | |
| 01 | PC and load and store address tracing only | | | | | | | | | | | | | | | |
| 10 | PC, load and store address, and load and store data | | | | | | | | | | | | | | | |
| 11 | Reserved | | | | | | | | | | | | | | | |
| TBI | 4 | <p>This bit indicates how many trace buffers are implemented by the TCB, as follows:</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Only one trace buffer is implemented, and the TBU bit of this register indicates which trace buffer is implemented</td></tr><tr><td>1</td><td>Both on-chip and off-chip trace buffers are implemented by the TCB and the TBU bit of this register indicates to which trace buffer the traces is currently written.</td></tr></table> <p>This bit is loaded from the <i>PDI_TBImpl</i> signal when the <i>PDI_SyncOffEn</i> signal is asserted.</p> | Encoding | Meaning | 0 | Only one trace buffer is implemented, and the TBU bit of this register indicates which trace buffer is implemented | 1 | Both on-chip and off-chip trace buffers are implemented by the TCB and the TBU bit of this register indicates to which trace buffer the traces is currently written. | R | Undefined | | | | | | |
| Encoding | Meaning | | | | | | | | | | | | | | | |
| 0 | Only one trace buffer is implemented, and the TBU bit of this register indicates which trace buffer is implemented | | | | | | | | | | | | | | | |
| 1 | Both on-chip and off-chip trace buffers are implemented by the TCB and the TBU bit of this register indicates to which trace buffer the traces is currently written. | | | | | | | | | | | | | | | |
| TBU | 3 | <p>This bit denotes to which trace buffer the trace is currently being written and is used to select the appropriate interpretation of the <i>TraceControl2_{SYP}</i> field.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Trace data is being sent to an on-chip trace buffer</td></tr><tr><td>1</td><td>Trace Data is being sent to an off-chip trace buffer</td></tr></table> <p>This bit is loaded from the <i>PDI_OffChipTB</i> signal when the <i>PDI_SyncOffEn</i> signal is asserted.</p> | Encoding | Meaning | 0 | Trace data is being sent to an on-chip trace buffer | 1 | Trace Data is being sent to an off-chip trace buffer | R | Undefined | | | | | | |
| Encoding | Meaning | | | | | | | | | | | | | | | |
| 0 | Trace data is being sent to an on-chip trace buffer | | | | | | | | | | | | | | | |
| 1 | Trace Data is being sent to an off-chip trace buffer | | | | | | | | | | | | | | | |

Table 6.38 TraceControl2 Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | |
|--------|-----------------|---|--------------|-------------|-----|----------------|-----|----------------|-----|----------------|-----|----------------|-----|----------------|-----|-----------------|-----|-----------------|-----|-----------------|---|-----------|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | |
| SyP | 2:0 | <div>The period (in cycles) to which the internal synchronization counter is reset when tracing is started, or when the synchronization counter has overflowed.</div> <table><thead><tr><th>SyP</th><th>Sync Period</th></tr></thead><tbody><tr><td>000</td><td>2⁵</td></tr><tr><td>001</td><td>2⁶</td></tr><tr><td>010</td><td>2⁷</td></tr><tr><td>011</td><td>2⁸</td></tr><tr><td>100</td><td>2⁹</td></tr><tr><td>101</td><td>2¹⁰</td></tr><tr><td>110</td><td>2¹¹</td></tr><tr><td>111</td><td>2¹²</td></tr></tbody></table> <div>This field is loaded from the <i>PDI_SyncPeriod</i> signal when the <i>PDI_SyncOffEn</i> signal is asserted.</div> | SyP | Sync Period | 000 | 2 ⁵ | 001 | 2 ⁶ | 010 | 2 ⁷ | 011 | 2 ⁸ | 100 | 2 ⁹ | 101 | 2 ¹⁰ | 110 | 2 ¹¹ | 111 | 2 ¹² | R | Undefined |
| SyP | Sync Period | | | | | | | | | | | | | | | | | | | | | |
| 000 | 2 ⁵ | | | | | | | | | | | | | | | | | | | | | |
| 001 | 2 ⁶ | | | | | | | | | | | | | | | | | | | | | |
| 010 | 2 ⁷ | | | | | | | | | | | | | | | | | | | | | |
| 011 | 2 ⁸ | | | | | | | | | | | | | | | | | | | | | |
| 100 | 2 ⁹ | | | | | | | | | | | | | | | | | | | | | |
| 101 | 2 ¹⁰ | | | | | | | | | | | | | | | | | | | | | |
| 110 | 2 ¹¹ | | | | | | | | | | | | | | | | | | | | | |
| 111 | 2 ¹² | | | | | | | | | | | | | | | | | | | | | |

6.2.31 User Trace Data Register (CP0 Register 23, Select 3)

A software write to any bits in the *UserTraceData* register will trigger a trace record to be written indicating a type 1 or type 2 user format. The type is based on the *UT* bit in the *TraceControl* register. This register cannot be written in consecutive cycles. The trace output data is **UNPREDICTABLE** if this register is written in consecutive cycles.

This register is only implemented if the MIPS Trace capability is present.

Figure 6.32 User Trace Data Register Format

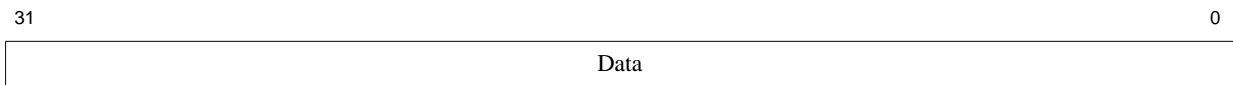


Table 6.39 UserTraceData Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| Data | 31:0 | Software readable/writable data. When written, this triggers a user format trace record out of the PDtrace interface that transmits the Data field to trace memory. | R/W | 0 |

6.2.32 TracerBPC Register (CP0 Register 23, Select 4)

The *TracerBPC* register is used to control start and stop of tracing using an EJTAG Instruction Hardware breakpoint. The Instruction Hardware breakpoint would then be set as a trigger source and optionally also as a Debug exception breakpoint.

This register is only implemented if both Hardware breakpoints and the MIPS Trace capability are present.

Figure 6.33 TracerBPC Register Format



Table 6.40 TracerBPC Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | |
|-------------------|--------------|--|--------------|-------------|---|
| Name | Bits | | | | |
| 0 | 31:29, 27:12 | Reserved for future implementation. | R | 0/1 | |
| IE | 28 | Used to specify whether the trigger signal from EJTAG instruction breakpoint should trigger tracing functions or not: | R/W | 0 | |
| | | Encoding | | | Meaning |
| | | 0 | | | Disables trigger signals from instruction breakpoints |
| | | 1 | | | Enables trigger signals from instruction breakpoints |
| IBPC _n | 3n+2:3n | The three bits are decoded to enable different tracing modes. Table 6.42 shows the possible interpretations. Each set of 3 bits represents the encoding for the instruction breakpoint <i>n</i> in the EJTAG implementation, if it exists. If the breakpoint does not exist, then the bits are reserved, read as zero, and writes are ignored. | R/W | 0 | |

6.2.33 TraceDBPC Register (CP0 Register 23, Select 5)

The *TraceDBPC* register is used to control start and stop of tracing using an EJTAG Data Hardware breakpoint. The Data Hardware breakpoint would then be set as a trigger source and optionally also as a Debug exception breakpoint.

This register is only implemented if both Hardware breakpoints and the MIPS Trace capability are present.

Figure 6.34 TraceDBPC Register Format

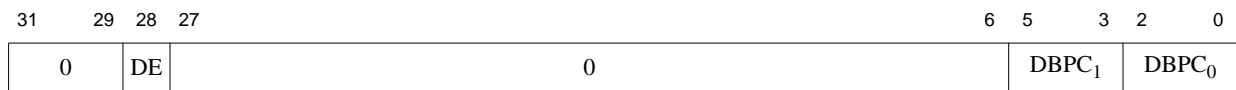


Table 6.41 TraceDBPC Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|----------------|------------------------------------|--------------|-------------|
| Name | Bits | | | |
| 0 | 31:29, 27:6 | Reserved for future implementation | R | 0/1 |

Table 6.41 TraceDBPC Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|-------------------|--|---|--------------|-------------|---|--|---|---|-----|---|
| Name | Bits | | | | | | | | | |
| DE | 28 | Used to specify whether the trigger signal from EJTAG data breakpoint should trigger tracing functions or not: <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Disables trigger signals from data breakpoints</td></tr><tr><td>1</td><td>Enables trigger signals from data breakpoints</td></tr></table> | Encoding | Meaning | 0 | Disables trigger signals from data breakpoints | 1 | Enables trigger signals from data breakpoints | R/W | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | Disables trigger signals from data breakpoints | | | | | | | | | |
| 1 | Enables trigger signals from data breakpoints | | | | | | | | | |
| DBPC _n | 3n+2:3n | The three bits are decoded to enable different tracing modes. Table 6.42 shows the possible interpretations. Each set of 3 bits represents the encoding for the data breakpoint <i>n</i> in the EJTAG implementation, if it exists. If the breakpoint does not exist then the bits are reserved, read as zero and writes are ignored. | R/W | 0 | | | | | | |

Table 6.42 BreakPoint Control Modes: IBPC and DBPC

| Value | Trigger Action | Description |
|------------|---------------------------|--|
| 000 | Unconditional Trace Stop | Unconditionally stop tracing if tracing was turned on. If tracing is already off, then there is no effect. |
| 001 | Unconditional Trace Start | Unconditionally start tracing if tracing was turned off. If tracing is already turned on, then there is no effect. |
| 010 to 111 | Not used | Reserved for future implementation |

6.2.34 Debug Exception Program Counter Register (CP0 Register 24, Select 0)

The Debug Exception Program Counter (*DEPC*) register is a read/write register that contains the address at which processing resumes after a debug exception or debug mode exception has been serviced.

For synchronous (precise) debug and debug mode exceptions, the *DEPC* contains either:

- The virtual address of the instruction that was the direct cause of the debug exception, or
- The virtual address of the immediately preceding branch or jump instruction, when the debug exception causing instruction is in a branch delay slot, and the Debug Branch Delay (*DBD*) bit in the *Debug* register is set.

For asynchronous debug exceptions (debug interrupt), the *DEPC* contains the virtual address of the instruction where execution should resume after the debug handler code is executed.

In processors that implement the MIPS16 ASE, a read of the *DEPC* register (via MFC0) returns the following value in the destination GPR:

$$\text{GPR}[\text{rt}] \leftarrow \text{DebugExceptionPC}_{31..1} \parallel \text{ISAMode}_0$$

That is, the upper 31 bits of the debug exception PC are combined with the lower bit of the *ISAMode* field and written to the GPR.

Similarly, a write to the *DEPC* register (via MTC0) takes the value from the GPR and distributes that value to the debug exception PC and the ISA Mode field, as follows

$$\begin{aligned}\text{DebugExceptionPC} &\leftarrow \text{GPR}[\text{rt}]_{31..1} \parallel 0 \\ \text{ISAMode} &\leftarrow 2\#0 \parallel \text{GPR}[\text{rt}]_0\end{aligned}$$

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the debug exception PC, and the lower bit of the debug exception PC is cleared. The upper bit of the *ISAMode* field is cleared and the lower bit is loaded from the lower bit of the GPR.

Figure 6.35 DEPC Register Format



Table 6.43 DEPC Register Formats

| Fields | | Description | Read / Write | Reset |
|--------|--------|--|--------------|-----------|
| Name | Bit(s) | | | |
| DEPC | 31:0 | The <i>DEPC</i> register is updated with the virtual address of the instruction that caused the debug exception. If the instruction is in the branch delay slot, then the virtual address of the immediately preceding branch or jump instruction is placed in this register. Execution of the DERET instruction causes a jump to the address in the <i>DEPC</i> . | R/W | Undefined |

6.2.35 Performance Counter Register (CP0 Register 25, select 0-3)

The 24K processor defines two performance counters and two associated control registers, which are mapped to CP0 register 25. The select field of the MTC0/MFC0 instructions are used to select the specific register accessed by the instruction, as shown in Table 6.44.

Table 6.44 Performance Counter Register Selects

| Select[2:0] | Register |
|-------------|--------------------|
| 0 | Register 0 Control |
| 1 | Register 0 Count |
| 2 | Register 1 Control |
| 3 | Register 1 Count |

Each counter is a 32-bit read/write register and is incremented by one each time the countable event, specified in its associated control register, occurs. Each counter can independently count one type of event at a time.

Bit 31 of each of the counters are AND'ed with an interrupt enable bit, *IE*, of their respective control register to determine if a performance counter interrupt should be signalled. The two values are then OR'ed together to create the *SI_PCI* output. This signal is combined with one of the *SI_Int* pins to signal an interrupt to the core. Counting is not affected by the interrupt indication. This output is cleared when the counter wraps to zero, and may be cleared in software by writing a value with bit 31 = 0 to the *Performance Counter Count* registers.

NOTE: the performance counter registers are connected to a clock that is stopped when the processor is in sleep mode (if the top level clock gater is present). Most events would not be active during that time, but others would be, notably the cycle count. This behavior should be considered when analyzing measurements taken on a system. Further, note that FPGA implementations of the core would generally not have the clock gater present and thus would have different behavior than a typical ASIC implementation.

For a more detailed description of performance counter events, refer to *Programming the 24K Core Family* [7].

Figure 6.36 Performance Counter Control Register

| | | | | | | | | | | |
|----|---|----|----|-------|----|---|---|---|-----|---|
| 31 | | 12 | 11 | | 5 | 4 | 3 | 2 | 1 | 0 |
| M | 0 | | | Event | IE | U | S | K | EXL | |

Table 6.45 Performance Counter Control Register Field Descriptions

| Fields | | Description | Read/ Write | Reset State |
|--------|-----------|---|----------------|-------------|
| Name | Bits | | | |
| M | 31 | If this bit is one, another pair of <i>Performance Control</i> and <i>Counter</i> registers is implemented at a MTC0 or MFC0 select field value of 'n+2' and 'n+3'. | R | Preset |
| Event | 11:5 | Counter event enabled for this counter. Possible events are listed in Table 6.46 . | R/W | Undefined |
| IE | 4 | Counter Interrupt Enable. This bit masks bit 31 of the associated count register from the interrupt exception request output. | R/W | 0 |
| U | 3 | Count in User Mode. When this bit is set, the specified event is counted in User Mode. | R/W | Undefined |
| S | 2 | Count in Supervisor Mode. When this bit is set, the specified event is counted in Supervisor Mode. | R/W | Undefined |
| K | 1 | Count in Kernel Mode. When this bit is set, count the event in Kernel Mode when <i>EXL</i> and <i>ERL</i> both are 0. | R/W | Undefined |
| EXL | 0 | Count when <i>EXL</i> . When this bit is set, count the event when <i>EXL</i> = 1 and <i>ERL</i> = 0. | R/W | Undefined |
| 0 | 30, 15:12 | Must be written as zeroes; returns zeroes when read. | 0 | 0 |

[Table 6.46](#) describes the events countable with the two performance counters. The mode column indicates whether the event counting is influenced by the mode bits (U,S,K,EXL) The operation of a counter is **UNPREDICTABLE** for events which are specified as Reserved. The performance counter resets to a low-power state, in which none of the

Table 6.46 Performance Counter Count Register Field Descriptions

| Event Num | Counter 0 | Mode | Counter 1 | Mode |
|-----------|------------------------------|------|------------------------|------|
| 0 | Cycles | No | Cycles | No |
| 1 | Instructions completed | Yes | Instructions completed | Yes |
| 2 | branch instructions | Yes | Branch mispredictions | Yes |
| 3 | JR r31 (return) instructions | Yes | JR r31 mispredictions | Yes |
| 4 | JR (not r31) instructions | Yes | JR r31 not predicted | Yes |

Table 6.46 Performance Counter Count Register Field Descriptions

| Event Num | Counter 0 | Mode | Counter 1 | Mode |
|-----------|---------------------------------|------|--|------|
| 5 | ITLB accesses | Yes | ITLB misses | Yes |
| 6 | DTLB accesses | Yes | DTLB misses | Yes |
| 7 | JTLB instruction accesses | Yes | JTLB instruction misses | Yes |
| 8 | JTLB data accesses | Yes | JTLB data misses | Yes |
| 9 | Instruction Cache accesses | Yes | Instruction cache misses | Yes |
| 10 | Data cache accesses | Yes | Data cache writebacks | Yes |
| 11 | Data cache misses | Yes | Data cache misses | Yes |
| 12 | Reserved | Yes | Reserved | Yes |
| 13 | Store Misses | Yes | Load Misses | Yes |
| 14 | integer instructions completed | Yes | FPU instructions completed | Yes |
| 15 | loads completed | Yes | stores completed | Yes |
| 16 | J/JAL completed | Yes | MIPS16 instructions completed | Yes |
| 17 | no-ops completed | Yes | integer multiply/divide completed | Yes |
| 18 | Stall cycles | No | replay traps (other than uTLB) | Yes |
| 19 | SC instructions completed | Yes | SC instructions failed | Yes |
| 20 | Prefetch instructions completed | Yes | Prefetch instructions completed with cache hit | Yes |
| 21 | L2 cache writebacks | No | L2 cache accesses | No |
| 22 | L2 cache misses | No | L2 cache single bit errors corrected | No |
| 23 | Exceptions taken | Yes | Reserved | Yes |
| 24 | cache fixup | Yes | Reserved | Yes |
| 25 | IFU stall cycles | No | ALU stall cycles | No |
| 26 | Reserved | Yes | Reserved | Yes |
| 27 | Reserved | Yes | Reserved | Yes |
| 28 | Reserved | Yes | Impl. specific Cp2 event | Yes |
| 29 | Impl. specific ISPRAM event | Yes | Impl. specific DSPRAM event | Yes |
| 30 | Impl. specific CorExtend event | Yes | Reserved | Yes |
| 31 | Reserved | Yes | Reserved | Yes |
| 32 | Reserved | Yes | Reserved | Yes |
| 33 | Uncached Loads | Yes | Uncached Stores | Yes |
| 34 | Reserved | Yes | Reserved | Yes |
| 35 | CP2 Arithmetic Instns Completed | No | CP2 To/From Instns completed | Yes |

Table 6.46 Performance Counter Count Register Field Descriptions

| Event Num | Counter 0 | Mode | Counter 1 | Mode |
|-----------|---|------|---|------|
| 36 | Reserved | | | |
| 37 | I\$ Miss stall cycles | Yes | D\$ miss stall cycles | Yes |
| 38 | SYNC stalls | Yes | FSB Index Conflicts | Yes |
| 39 | D\$ miss cycles | No | L2 miss cycles | No |
| 40 | Uncached stall cycles | Yes | Reserved | Yes |
| 41 | MDU stall cycles | Yes | FPU stall cycles | Yes |
| 42 | CP2 stall cycles | Yes | CorExtend stall cycles | Yes |
| 43 | ISPRAM stall cycles | Yes | DSPRAM stall cycles | Yes |
| 44 | CACHE Instn stall cycles | No | Reserved | Yes |
| 45 | Load to Use stall cycles | Yes | ALU to AGEN stall cycles | Yes |
| 46 | Other interlock stall cycles | Yes | Branch mispredict stall cycles | No |
| 47 | Reserved | Yes | Reserved | Yes |
| 48 | IFU FB full refetches | Yes | FB entry allocated | No |
| 49 | EJTAG Instruction Triggerpoints | Yes | EJTAG Data Triggerpoints | Yes |
| 50 | FSB < 1/4 full | No | FSB 1/4-1/2 full | No |
| 51 | FSB > 1/2 full | No | FSB full pipeline stall cycles | No |
| 52 | LDQ < 1/4 full | No | LDQ 1/4-1/2 full | No |
| 53 | LDQ > 1/2 full | No | LDQ full pipeline stall cycles | No |
| 54 | WBB < 1/4 full | No | WBB 1/4-1/2 full | No |
| 55 | WBB > 1/2 full | No | WBB full pipeline stall cycles | No |
| 56-63 | Reserved | | | |
| 64 | SI_PCEvent[0] - System specific event 0 | No | SI_PCEvent[1] - System specific event 1 | No |
| 65 | SI_PCEvent[2] - System specific event 2 | No | SI_PCEvent[3] - System specific event 3 | No |
| 66 | SI_PCEvent[4] - System specific event 4 | No | SI_PCEvent[5] - System specific event 5 | No |
| 67 | SI_PCEvent[6] - System specific event 6 | No | SI_PCEvent[7] - System specific event 7 | No |
| 68-127 | Reserved | | | |
| 56-63 | Reserved | | | |

Table 6.47 Event Descriptions

| Event Name | Counter | Event Number | Description |
|--|---------|--------------|---|
| Cycles | 0/1 | 0 | Total number of cycles. The performance counters are clocked by the top-level gated clock. If the core is built with that clock gater present, none of the counters will increment while the clock is stopped - due to a WAIT instruction. |
| Instruction Completion: The following events indicate completion of various types of instructions | | | |
| Instructions | 0/1 | 1 | Total number of instructions completed. |
| Branch instns | 0 | 2 | Counts all branch instructions that completed. |
| JR R31 (return) instns | 0 | 3 | Counts all JR R31 instructions that completed. |
| JR (not R31) | 0 | 4 | Counts all JR \$xx (not \$31) and JALR instructions (indirect jumps). |
| Integer instns | 0 | 14 | Non-floating point, non-Coprocessor 2 instructions. |
| FPU instns | 1 | 14 | Floating point instructions. |
| Loads | 0 | 15 | Includes both integer and coprocessor loads. |
| Stores | 1 | 15 | Includes both integer and coprocessor stores. |
| J/JAL | 0 | 16 | Direct Jump (And Link) instruction. |
| MIPS16e | 1 | 16 | All MIPS16e instruction. |
| no-ops | 0 | 17 | This includes all instructions that normally write to a GPR, but where the destination register was set to r0. |
| Integer Multiply/Divide | 1 | 17 | Counts all Integer Multiply/Divide instructions (MULxx, DIVx, MADDx, MSUBx). |
| SC | 0 | 19 | Counts conditional stores regardless of whether they succeeded. |
| PREF | 0 | 20 | Note that this only counts PREFs that are actually attempted. PREFs to uncached addresses or ones with translation errors are not counted |
| Uncached Loads | 0 | 33 | Include both Uncached and Uncached Accelerated CCAs. |
| Uncached Stores | 1 | 33 | |
| Cp2 Arithmetic instns | 0 | 35 | Counts Coprocessor 2 register-to-register instructions. |
| Cp2 To/From instns | 1 | 35 | Includes move to/from, control to/from, and cop2 loads and stores. |
| Instruction execution events | | | |
| Branch mispredicts | 1 | 2 | Counts all branch instructions which completed, but were mispredicted. |
| JR r31 mispredicts | 1 | 3 | Counts all JR \$31 instructions which completed, used the RPS for a prediction, but were mispredicted. |
| JR r31 not-predicted | 1 | 4 | If RPS use is disabled, JR \$31 will not be predicted. |
| ITLB accesses | 0 | 5 | Counts ITLB accesses that are due to fetches showing up in IF stage of the pipe and do not use fixed mapping or are not in unmapped space. If an address is fetched twice down the pipe (as in the case of a cache miss), that instruction will count 2 ITLB accesses. Also, since each fetch gets us 2 instructions, there is one access marked per double word. |

Table 6.47 Event Descriptions (Continued)

| Event Name | Counter | Event Number | Description |
|--------------------------------------|---------|--------------|---|
| ITLB misses | 1 | 5 | Counts all misses in ITLB except ones that are on the back of another miss. We cannot process back to back misses and thus those are ignored for this purpose. Also ignored if there is some form of address error. |
| DTLB accesses | 0 | 6 | Counts DTLB access including those in unmapped address spaces. |
| DTLB misses | 1 | 6 | Counts DTLB misses. Back to back misses that result in only one DTLB entry getting refilled are counted as a single miss. |
| JTLB instruction accesses | 0 | 7 | Instruction JTLB accesses are counted exactly the same as ITLB misses. |
| JTLB instruction misses | 1 | 7 | Counts instruction JTLB accesses that result in no match or a match on an invalid translation. |
| JTLB data accesses | 0 | 8 | Data JTLB accesses. |
| JTLB data misses | 1 | 8 | Counts data JTLB accesses that result in no match or a match on an invalid translation. |
| I\$ accesses | 0 | 9 | Counts every time the instruction cache is accessed. All replays, wasted fetches etc. are counted. For example, following a branch, even the prediction is taken, the fall through access is counted. |
| I\$ misses | 1 | 9 | Counts all instruction cache misses that result in a bus request. |
| D\$ accesses | 0 | 10 | Counts cached loads and stores. |
| D\$ writebacks | 1 | 10 | Counts cache lines written back to memory due to replacement or cacheops. |
| D\$ misses | 0/1 | 11 | Counts loads and stores that miss in the cache |
| Load Misses | 0 | 13 | Counts number of cacheable loads that miss in the cache. |
| Store Misses | 1 | 13 | Counts number of cacheable stores that miss in the cache. |
| SC instructions failed | 1 | 19 | SC instruction that did not update memory Note: While this event and the SC instruction count event can be configured to count in specific operating modes, the timing of the events is much different and the observed operating mode could change between them, causing some inaccuracy in the measured ratio. |
| PREF completed with cache hit | 1 | 20 | Counts PREF instructions that hit in the cache |
| L2 Cache Writebacks | 0 | 21 | Counts cache lines written back to memory due to replacement or cacheops |
| L2 Cache Accesses | 1 | 21 | Number of accesses to L2 Cache |
| L2 Cache Misses | 0 | 22 | Number of accesses that missed in the L2 cache |
| L2 Cache Single Bit Errors Corrected | 1 | 22 | Single bit errors in L2 Cache that were detected and corrected |
| Exceptions Taken | 0 | 23 | Any type of exception taken |
| EJTAG instruction triggers | 0 | 49 | Number of times an EJTAG Instruction Trigger Point condition matched |
| EJTAG data triggers | 1 | 49 | Number of times an EJTAG Data Trigger Point condition matched |
| Pipeline Fun | | | |

Table 6.47 Event Descriptions (Continued)

| Event Name | Counter | Event Number | Description |
|---|---------|--------------|--|
| Cache fixup | 0 | 24 | Counts cycles where the LSU is in fixup and cannot accept a new instruction from the ALU. Fixups are replays within the LSU that occur when an instruction needs to re-access the cache or the DTLB |
| General Stalls | | | |
| IFU stall cycles | 0 | 25 | Counts the number of cycles where the fetch unit is not providing a valid instruction to the ALU. |
| ALU stall cycles | 1 | 25 | Counts the number of cycles where the ALU pipeline cannot advance. |
| Stall cycles | 0 | 18 | Counts the total number of cycles where no instructions are issued by IFU to ALU (the RF stage does not advance). This includes both of the previous two events. This is different than the sum of them though because cycles when both stalls are active will only be counted once. |
| Specific stalls - these events will count the number of cycles lost due to this. This will include bubbles introduced by replays within the pipe. If multiple stall sources are active simultaneously, the counters for each of the active events will be incremented. | | | |
| SYNC stall cycles | 0 | 38 | Cycles where the main pipeline is stalled waiting for a SYNC to complete |
| FSB index conflict stall cycles | 1 | 38 | Cycles where the main pipeline is stalled because of an index conflict in the Fill Store Buffer. |
| I\$ miss stall cycles | 0 | 37 | Cycles when IFU stalls because an I\$ miss caused the IFU not to have any runnable instructions. Ignores the stalls due to ITLB misses as well as the 4 cycles following a redirect. |
| D\$ miss stall cycles | 1 | 37 | Counts all cycles where integer pipeline waits on Load return data due to a D-cache miss. The LSU can signal a “long stall” on a D-cache misses, in which case the waiting TC might be rescheduled so other TCs can execute instructions till the data returns. |
| D\$ miss cycle cycles | 0 | 39 | D\$ miss is outstanding, but not necessarily stalling the pipeline. The difference between this and D\$ miss stall cycles can show the gain from non-blocking cache misses. |
| L2 miss cycles | 1 | 39 | L2 miss is outstanding, but not necessarily stalling the pipeline. |
| Uncached stall cycles | 0 | 40 | Cycles where the processor is stalled on an uncached fetch, load, or store. |
| MDU stall cycles | 0 | 41 | Counts all cycles where integer pipeline waits on MDU return data. |
| FPU stall cycles | 1 | 41 | Counts all cycles where integer pipeline waits on FPU return data. |
| Cp2 stall cycles | 0 | 42 | Counts all cycles where integer pipeline waits on CP2 return data. |
| CorExtend stall cycles | 1 | 42 | Counts all cycles where integer pipeline waits on CorExtend return data. |
| ISPRAM stall cycles | 0 | 43 | Count all pipeline bubbles that are a result of multicycle ISPRAM access. Pipeline bubbles are defined as all cycles that IFU doesn't present an instruction to ALU. The four cycles after a redirect are not counted. |
| DSPRAM stall cycles | 1 | 43 | Counts stall cycles created by an instruction waiting for access to DSPRAM. |

Table 6.47 Event Descriptions (Continued)

| Event Name | Counter | Event Number | Description | | | | | | | | | | | | |
|---|----------------|------------------|---|-------|----------------|------------------|-------|---|-----|---------|-----|-----|-------|----|----|
| CACHE instn stall cycles | 0 | 44 | Counts all cycles where pipeline is stalled due to CACHE instructions. Includes cycles where CACHE instructions themselves are stalled in the ALU, and cycles where CACHE instructions cause subsequent instructions to be stalled. | | | | | | | | | | | | |
| Load to Use stall cycles | 0 | 45 | Counts all cycles where integer pipeline waits on Load return data. | | | | | | | | | | | | |
| ALU to AGEN stall cycles | 1 | 45 | Counts stall cycles due to skewed ALU where the bypass to the address generation takes an extra cycle. | | | | | | | | | | | | |
| Other interlocks stall cycles | 0 | 46 | Counts all cycles where integer pipeline waits on return data from MFC0, RDHWR instructions. | | | | | | | | | | | | |
| Branch mispredict stalls cycles | 1 | 46 | This counts the number of cycles from a mispredicted branch until the next non-delay slot instruction executes. | | | | | | | | | | | | |
| FSB full pipeline stall cycles | 1 | 51 | Cycles where the pipeline is stalled because the Fill-Store Buffer in LSU is full. | | | | | | | | | | | | |
| LDQ full pipeline stall cycles | 1 | 53 | Cycles where the pipeline is stalled because the Load Data Queue in the LSU is full. | | | | | | | | | | | | |
| Write Back Buffer full stall cycles | 1 | 55 | Cycles where the pipeline is stalled because the WriteBack Buffer in the BIU is full. | | | | | | | | | | | | |
| Latency Events - These events provide a statistical sampling of latencies within the system. One particular FSB entry is monitored. The latency event increments each cycle from the time a request is generated until response is seen. The count events are incremented once for each request that we are counting the latency for. | | | | | | | | | | | | | | | |
| Request Latency to Read Response | 0 | 61 | Measures latency from miss detection until critical dword of response is returned, Only counts for cacheable reads. | | | | | | | | | | | | |
| Request Count for RR Latency | 1 | 61 | Counts number of cacheable read requests used for previous latency counter. | | | | | | | | | | | | |
| Implementation specific events - Modules that can be replaced by the customer will have an event signal associated with them. | | | | | | | | | | | | | | | |
| Cp2 | 1 | 28 | | | | | | | | | | | | | |
| ISPRAM | 0 | 29 | | | | | | | | | | | | | |
| DSPRAM | 1 | 29 | | | | | | | | | | | | | |
| CorExtend | 0 | 30 | | | | | | | | | | | | | |
| SI_PCEvent[7:0] | 0/1 | 64-67 | | | | | | | | | | | | | |
| Buffer usage events - These count the number of cycles that buffers within the core spend at various levels of fullness. | | | | | | | | | | | | | | | |
| Fill Store Buffer < 1/4 full | 0 | 50 | Buffer Occupancy: The following table shows what values fall into each of the bins for the different buffer sizes that can be chosen. | | | | | | | | | | | | |
| Fill Store Buffer 1/4 to 1/2 full | 1 | 50 | | | | | | | | | | | | | |
| Fill Store Buffer > 1/2 full | 0 | 51 | | | | | | | | | | | | | |
| Load Data Queue < 1/4 full | 0 | 52 | | | | | | | | | | | | | |
| Load Data Queue 1/4 to 1/2 full | 1 | 52 | | | | | | | | | | | | | |
| Load Data Queue > 1/2 full | 0 | 53 | | | | | | | | | | | | | |
| Write Back Buffer < 1/4 full | 0 | 54 | | | | | | | | | | | | | |
| Write Back Buffer 1/4 to 1/2 full | 1 | 54 | | | | | | | | | | | | | |
| Write Back Buffer > 1/2 full | 0 | 55 | | | | | | | | | | | | | |
| | | | <table><tr><th>State</th><th>4 Entry Buffer</th><th>8/9 Entry Buffer</th></tr><tr><td>< 1/4</td><td>0</td><td>0-1</td></tr><tr><td>1/4-1/2</td><td>1-2</td><td>2-4</td></tr><tr><td>> 1/2</td><td>3+</td><td>5+</td></tr></table> | State | 4 Entry Buffer | 8/9 Entry Buffer | < 1/4 | 0 | 0-1 | 1/4-1/2 | 1-2 | 2-4 | > 1/2 | 3+ | 5+ |
| State | 4 Entry Buffer | 8/9 Entry Buffer | | | | | | | | | | | | | |
| < 1/4 | 0 | 0-1 | | | | | | | | | | | | | |
| 1/4-1/2 | 1-2 | 2-4 | | | | | | | | | | | | | |
| > 1/2 | 3+ | 5+ | | | | | | | | | | | | | |

Table 6.47 Event Descriptions (Continued)

| Event Name | Counter | Event Number | Description |
|---|---------|--------------|--|
| IFU Fill buffer allocated | 1 | 48 | Number of cycles where at least one of the IFU fill buffers is allocated (miss pending) |
| Refetches due to all IFU Fill Buffers allocated | 0 | 48 | Counts the number of times an instruction cache miss was detected, but both fill buffers were already allocated. |

counters will start counting events until software has enabled event counting, using an MTC0 instruction to the Performance Counter Control Registers.

Figure 6.37 Performance Counter Count Register

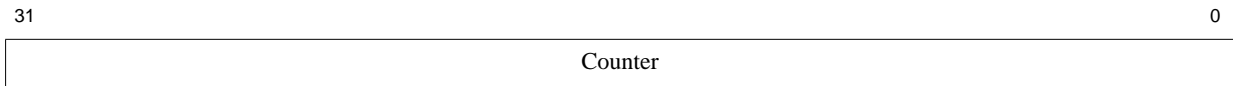


Table 6.48 Performance Counter Count Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|------|-------------|--------------|-------------|
| Name | Bits | | | |
| Counter | 31:0 | Counter | R/W | Undefined |

6.2.36 ErrCtl Register (CP0 Register 26, Select 0)

The *ErrCtl* register controls parity protection of data and instruction caches and provides for software testing of the way-selection and scratchpad RAMs.

Parity protection can be enabled or disabled using the *PE* bit. When parity is enabled and the *PO* bit is deasserted, the CACHE Index Store Tag and Index Store Data operations will internally generate parity to be written into the RAM arrays. However, when the *PO* bit is asserted, tag array parity is written using the *P* bit of the *TagLo* register and data array parity is written using the *PI/PD* bits of *ErrCtl*.

ECC protection for the secondary cache is controlled by a combination of *PE* and the *L2P* bits.

A CACHE Index Load Tag operation to the instruction cache will update the *PCI* field with the instruction precode bits from the data array and the *PI* field with the parity bits from the data array if parity is supported. A CACHE Index Load Tag operation to the data cache will cause the *PD* bits to be updated with the byte parity for the selected word of the data array if parity is implemented. If parity is disabled or not implemented, the contents of the *PI* and *PD* fields after a CACHE Index Load Tag operation will be 0.

The *PCO* field can be used for testing the precode bits of the instruction cache data array. When the *PCO* bit is cleared, the CACHE Index Store Data instruction will internally generate the precode bits to be written into the instruction cache data array. However, when the *PCO* bit is set, the CACHE Index Store Data instruction will write the value in the *PCI* field to the precode bits in the data array. Setting an illegal value in the precode bits will cause unpredictable behavior. This mechanism should only be used for software testing of the cache arrays. Furthermore, the cache should be flushed after testing.

The way- selection RAM test mode is enabled by setting the *WST* bit. This mode is intended for software testing of the way-selection RAM and data RAM. It modifies the functionality of the CACHE Index Load Tag and Index Store

Tag operations so that they modify the way-selection RAM instead of the TAG RAMs. In addition, when the *WST* bit is set, the CACHE Index Store Data can be used for testing the data RAM.

Setting the *SPR* bit enables scratchpad test mode. This mode allows reading and writing of the scratchpad pseudo-tags as well the scratchpad data array.

At most one of the *WST* and *SPR* bits should be set. Setting multiple bits will lead to unpredictable behavior. Refer to “CACHE” on page 329 for a description of CACHE instruction operation for the different values of these bits.

Figure 6.38 ErrCtl Register

| | | | | | | | | | | | | | | | | | | | | |
|----|----|-----|-----|-----|----|-----|------|-----|----|----|----|-----|----|--|----|----|--|----|---|---|
| 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | | 13 | 12 | | 4 | 3 | 0 |
| PE | PO | WST | SPR | PCO | 0 | LBE | WABE | L2P | 0 | SE | FE | PCI | | | PI | | | PD | | |

Table 6.49 ErrCtl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|----------------------------|--|--------------|-------------|---|-----------------------|---|----------------------------|----------|---|
| Name | Bits | | | | | | | | | |
| PE | 31 | <p>Parity Enable. This bit enables or disables the cache parity protection for both the instruction cache and the data cache.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Parity disabled</td></tr><tr><td>1</td><td>Parity enabled</td></tr></table> <p>This field is only write-able if the cache parity option was implemented when the core was built. If cache parity is not supported, this field is always read as 0. Software can test for cache parity support by attempting to write a 1 to this field, then read back the value.</p> | Encoding | Meaning | 0 | Parity disabled | 1 | Parity enabled | R or R/W | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | Parity disabled | | | | | | | | | |
| 1 | Parity enabled | | | | | | | | | |
| PO | 30 | <p>Parity Overwrite. If set, the <i>PI/PD</i> fields of this register overwrites calculated parity for the data array. In addition, the <i>P</i> field of the <i>TagLo</i> register overwrites calculated parity for the tag array. This bit only has significance during CACHE Index Store Tag and CACHE Index Store Data operations.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Use calculated parity</td></tr><tr><td>1</td><td>Override calculated parity</td></tr></table> | Encoding | Meaning | 0 | Use calculated parity | 1 | Override calculated parity | R/W | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | Use calculated parity | | | | | | | | | |
| 1 | Override calculated parity | | | | | | | | | |
| WST | 29 | <p>Way Selection Test. If set, way-selection RAM test mode is enabled. This affects only the CACHE instruction operation. CACHE instruction behavior is undefined if this bit is set at the same time as <i>SPR</i>.</p> <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Test mode disabled</td></tr><tr><td>1</td><td>Test mode enabled</td></tr></table> | Encoding | Meaning | 0 | Test mode disabled | 1 | Test mode enabled | R/W | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | Test mode disabled | | | | | | | | | |
| 1 | Test mode enabled | | | | | | | | | |
| SPR | 28 | <p>ScratchPadRAM test. If set, indexed CACHE instructions operate on the ScratchPad RAM. Undefined behavior if ScratchPad RAM is not present or if this bit is set at the same time as <i>WST</i>.</p> | R/W | 0 | | | | | | |

Table 6.49 ErrCtl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | |
|----------|---|---|--------------|-------------|----------|---------------------------------------|------|---|-----|-----------|---|---|---|---|---|---|---|-----|---|
| Name | Bits | | | | | | | | | | | | | | | | | | |
| PCO | 27 | Precode override. If set, the contents of the <i>PCI</i> field overwrite the calculated precode bits when data is written to the instruction cache for CACHE IndexStoreData operations. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Use calculated precode</td></tr><tr><td>1</td><td>Override calculated precode</td></tr></table> | Encoding | Meaning | 0 | Use calculated precode | 1 | Override calculated precode | R/W | 0 | | | | | | | | | |
| Encoding | Meaning | | | | | | | | | | | | | | | | | | |
| 0 | Use calculated precode | | | | | | | | | | | | | | | | | | |
| 1 | Override calculated precode | | | | | | | | | | | | | | | | | | |
| ITC | 26 | InterThread Communication. If set, Index Load Tag and Index Store Tag CACHE instructions operate on the ITC tag. CACHE instruction behavior is undefined if this bit is set at the same time as <i>WST</i> or <i>SPR</i> . | R/W | 0 | | | | | | | | | | | | | | | |
| LBE | 25 | Bit indicating that the most recent Data Bus Error was involved a load instruction. A Per-TC <i>BE</i> bit will indicate which TCs were impacted. | R | Undefined | | | | | | | | | | | | | | | |
| WABE | 24 | Bit indicating that the most recent Data Bus Error was due to a write allocate and that store data was lost. There is no indication of which TC(s) the store request came from. It is possible for both <i>LBE</i> and <i>WABE</i> to be set if the bus error was on a line being used for both loads and stores. | R | Undefined | | | | | | | | | | | | | | | |
| L2P | 23 | L2 ECC Enable. This bit can be set only if the L2 is ECC-capable. This bit in conjunction with the <i>PE</i> bit enables or disables the ECC protection for the L2 cache: <table><tr><th>PE</th><th>L2P</th><th>L2 check</th></tr><tr><td>1</td><td>0</td><td>1</td></tr><tr><td>1</td><td>1</td><td>0</td></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>1</td></tr></table> | PE | L2P | L2 check | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | R/W | 0 |
| PE | L2P | L2 check | | | | | | | | | | | | | | | | | |
| 1 | 0 | 1 | | | | | | | | | | | | | | | | | |
| 1 | 1 | 0 | | | | | | | | | | | | | | | | | |
| 0 | 0 | 0 | | | | | | | | | | | | | | | | | |
| 0 | 1 | 1 | | | | | | | | | | | | | | | | | |
| 0 | 26,22:21 | Must be written as zeroes; returns zeroes when read. | 0 | 0 | | | | | | | | | | | | | | | |
| SE | 20 | Indicates that a second cache error was detected before the first error was processed. This is an unrecoverable error. This bit is set when a cache error is detected while the <i>FE</i> bit is set. This bit is cleared on reset or when a cache error is detected with <i>FE</i> cleared. | R | 0 | | | | | | | | | | | | | | | |
| FE | 19 | Indicates that this is the first cache error and therefore potentially recoverable. Error handling software should clear this bit when the error has been processed. This bit is cleared on reset. Refer to <i>SE</i> bit description for implications of this bit. | R/W | 0 | | | | | | | | | | | | | | | |
| PCI | 18:13 | Instruction precode bits read from or written to the instruction cache data RAM. | R/W | Undefined | | | | | | | | | | | | | | | |
| PI | 12:4 | Parity bit read from or written to instruction cache data RAM. <table><tr><th>Bits</th><th>Meaning</th></tr><tr><td>12</td><td>Even parity bit for the pre-code bits</td></tr><tr><td>11:4</td><td>Per-byte even parity bits for the 64b of data</td></tr></table> | Bits | Meaning | 12 | Even parity bit for the pre-code bits | 11:4 | Per-byte even parity bits for the 64b of data | R/W | Undefined | | | | | | | | | |
| Bits | Meaning | | | | | | | | | | | | | | | | | | |
| 12 | Even parity bit for the pre-code bits | | | | | | | | | | | | | | | | | | |
| 11:4 | Per-byte even parity bits for the 64b of data | | | | | | | | | | | | | | | | | | |

Table 6.49 ErrCtl Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| PD | 3:0 | Parity bits read from or written to data cache data RAM. <i>PD[0]</i> is even parity for the least-significant byte of the requested data. | R/W | Undefined |

6.2.37 CacheErr Register (CP0 Register 27, Select 0)

The *CacheErr* register provides an interface with the cache error-detection logic. When a Cache Error exception is signaled, the fields of this register are set accordingly. The format of the *CacheErr* register is different for Primary caches and the Secondary Cache. The *EC* bit ([30]) indicates the format to be used for decoding the contents of the *CacheErr* register.

Figure 6.39 CacheErr Register (Primary Caches)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----|----|----|----|----|----|----|----|----|----|-----|-------|----|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|---|
| 31 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | | | | | | | | | | | | | | | | | | 0 |
| ER | EC | ED | ET | ES | EE | EB | EF | SP | EW | Way | Index | | | | | | | | | | | | | | | | | | | |

Table 6.50 CacheErr Register Field Descriptions (Primary Caches)

| Fields | | Description | Read / Write | Reset State | |
|--------|------|---|--------------|-------------|----------------------------|
| Name | Bits | | | | |
| ER | 31 | Error Reference. Indicates the type of reference that encountered an error. | R | Undefined | |
| | | Encoding | | | Meaning |
| | | 0 | | | Instruction |
| | | 1 | | | Data |
| EC | 30 | Indicates the cache level at which the error was detected: | R | Undefined | |
| | | Encoding | | | Meaning |
| | | 0 | | | Primary |
| | | 1 | | | Non-primary |
| ED | 29 | Error Data. Indicates a data RAM error. | R | Undefined | |
| | | Encoding | | | Meaning |
| | | 0 | | | No data RAM error detected |
| | | 1 | | | Data RAM error detected |
| ET | 28 | Error Tag. Indicates a tag RAM error. | R | Undefined | |
| | | Encoding | | | Meaning |
| | | 0 | | | No tag RAM error detected |
| | | 1 | | | Tag RAM error detected |

Table 6.50 CacheErr Register Field Descriptions (Primary Caches) (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|----------------------------------|---|--------------|-------------|---|----------------------------------|---|-------------------------------|---|-----------|
| Name | Bits | | | | | | | | | |
| ES | 27 | Error source. Indicates whether error was caused by internal processor or external snoop request. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Error on internal request</td></tr><tr><td>1</td><td>Error on external request</td></tr></table> | Encoding | Meaning | 0 | Error on internal request | 1 | Error on external request | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Error on internal request | | | | | | | | | |
| 1 | Error on external request | | | | | | | | | |
| EE | 26 | Error external: Not supported. | R | 0 | | | | | | |
| EB | 25 | Error Both. Indicates that a data cache error occurred in addition to an instruction cache error. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No additional data cache error</td></tr><tr><td>1</td><td>Additional data cache error</td></tr></table> <p>In the case of an additional data cache error, the remainder of the bits in this register are set according to the instruction cache error.</p> | Encoding | Meaning | 0 | No additional data cache error | 1 | Additional data cache error | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No additional data cache error | | | | | | | | | |
| 1 | Additional data cache error | | | | | | | | | |
| EF | 24 | Error Fatal. Indicates that a fatal cache error has occurred. There are a few situations where software will not be able to get all information about a cache error from the <i>CacheErr</i> register. These situations are fatal because software cannot determine which memory locations have been affected by the error. To enable software to detect these cases, the <i>EF</i> bit (bit 24) has been added to the <i>CacheErr</i> register. <p>The following 6 cases are indicated as fatal cache errors by the <i>EF</i> bit:</p> <ol style="list-style-type: none">1 Dirty parity error in dirty victim (dirty bit cleared)2 Tag parity error in dirty victim3 Data parity error in dirty victim4 WB store miss and EW error at the requested index5 Dual/Triple errors from different transactions, e.g. scheduled and non-scheduled load.6 Multiple data cache errors detected before the first instruction of the cache error handler is issued. <p>In addition to the above, simultaneous instruction and data cache errors as indicated by <i>CacheErr_{EB}</i> will cause information about the data cache error to be unavailable. However, that situation is not indicated by <i>CacheErr_{EF}</i>.</p> | R | Undefined | | | | | | |
| SP | 23 | Scratchpad. Indicates Scratchpad RAM parity error. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No Scratchpad RAM error detected</td></tr><tr><td>1</td><td>Scratchpad RAM error detected</td></tr></table> | Encoding | Meaning | 0 | No Scratchpad RAM error detected | 1 | Scratchpad RAM error detected | R | 0 |
| Encoding | Meaning | | | | | | | | | |
| 0 | No Scratchpad RAM error detected | | | | | | | | | |
| 1 | Scratchpad RAM error detected | | | | | | | | | |

Table 6.50 CacheErr Register Field Descriptions (Primary Caches) (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|-------------------------------------|---|--------------|-------------|---|-------------------------------------|---|----------------------------------|---|-----------|
| Name | Bits | | | | | | | | | |
| EW | 22 | Error Way. Indicates a parity error on the dirty bits that are stored in the way selection RAM array.. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No way selection RAM error detected</td></tr><tr><td>1</td><td>Way selection RAM error detected</td></tr></table> | Encoding | Meaning | 0 | No way selection RAM error detected | 1 | Way selection RAM error detected | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No way selection RAM error detected | | | | | | | | | |
| 1 | Way selection RAM error detected | | | | | | | | | |
| Way | 21:20 | Way. Specifies the cache way in which the error was detected. It is not valid if a Tag RAM error is detected (<i>ET</i> =1) or Scratchpad RAM error is detected (<i>SP</i> =1). | R | Undefined | | | | | | |
| Index | 19:0 | Index. Specifies the cache or Scratchpad RAM index of the double word in which the error was detected. The way of the faulty cache is written by hardware in the <i>Way</i> field. Software must combine the <i>Way</i> and <i>Index</i> read in this register with cache configuration information in the <i>Config1</i> register in order to obtain an index which can be used in an indexed CACHE instruction to access the faulty cache data or tag. Note that <i>Index</i> is aligned as a byte index, so it does not need to be shifted by software before it is used in an indexed CACHE instruction. <i>Index</i> bits [4:3] are undefined upon tag RAM errors, and <i>Index</i> bits above the MSB actually used for cache indexing will also be undefined. Bits [19:16] are only used used for errors in the Scratchpad RAM. | R | Undefined | | | | | | |

Figure 6.40 CacheErr Register (Secondary Cache)

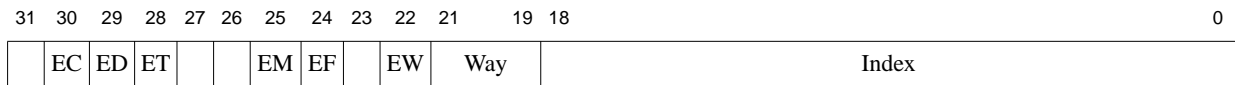


Table 6.51 CacheErr Register Field Descriptions (Secondary Cache)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|----------------------------|--|--------------|-------------|---|----------------------------|---|-------------------------|---|-----------|
| Name | Bits | | | | | | | | | |
| Reserved | 31 | Reserved | R | Undefined | | | | | | |
| EC | 30 | Indicates the cache level at which the error was detected: <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Primary</td></tr><tr><td>1</td><td>Non-primary</td></tr></table> | Encoding | Meaning | 0 | Primary | 1 | Non-primary | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | Primary | | | | | | | | | |
| 1 | Non-primary | | | | | | | | | |
| ED | 29 | Error Data. Indicates a data RAM error. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No data RAM error detected</td></tr><tr><td>1</td><td>Data RAM error detected</td></tr></table> | Encoding | Meaning | 0 | No data RAM error detected | 1 | Data RAM error detected | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No data RAM error detected | | | | | | | | | |
| 1 | Data RAM error detected | | | | | | | | | |

Table 6.51 CacheErr Register Field Descriptions (Secondary Cache) (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | |
|----------|-------------------------------------|---|--------------|-------------|---|-------------------------------------|---|----------------------------------|---|-----------|
| Name | Bits | | | | | | | | | |
| ET | 28 | Error Tag. Indicates a tag RAM error. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No tag RAM error detected</td></tr><tr><td>1</td><td>Tag RAM error detected</td></tr></table> | Encoding | Meaning | 0 | No tag RAM error detected | 1 | Tag RAM error detected | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No tag RAM error detected | | | | | | | | | |
| 1 | Tag RAM error detected | | | | | | | | | |
| Reserved | 27 | Reserved | R | Undefined | | | | | | |
| Reserved | 26 | Reserved | R | Undefined | | | | | | |
| EM | 25 | Error Multi. Indicates that a cache error occurred in multiple L2 arrays. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No multi error</td></tr><tr><td>1</td><td>Multi error</td></tr></table> <p>In the case of multiple errors, the Tag ram error has the highest priority, followed by the Data ram error, followed by the Way Select ram. Only the highest priority error information is recorded in the <i>CacheErr</i> register.</p> | Encoding | Meaning | 0 | No multi error | 1 | Multi error | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No multi error | | | | | | | | | |
| 1 | Multi error | | | | | | | | | |
| EF | 24 | Error Fatal. Indicates that a fatal cache error has occurred. There are a few situations where software will not be able to get all information about a cache error from the <i>CacheErr</i> register. These situations are fatal because software cannot determine which memory locations have been affected by the error. To enable software to detect these cases, the <i>EF</i> bit (bit 24) has been added to the <i>CacheErr</i> register. <p>This bit is set when a second L2 error occurs before taking the exception for the first L2 error.</p> | R | Undefined | | | | | | |
| Reserved | 23 | Reserved | R | Undefined | | | | | | |
| EW | 22 | Error Way. Indicates a way-selection RAM error. <table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No way-selection RAM error detected</td></tr><tr><td>1</td><td>Way-selection RAM error detected</td></tr></table> | Encoding | Meaning | 0 | No way-selection RAM error detected | 1 | Way-selection RAM error detected | R | Undefined |
| Encoding | Meaning | | | | | | | | | |
| 0 | No way-selection RAM error detected | | | | | | | | | |
| 1 | Way-selection RAM error detected | | | | | | | | | |
| Way | 21:19 | Way. Specifies the cache way in which the error was detected. It is not valid if a Tag RAM error is detected (<i>ET</i> =1) or Scratchpad RAM error is detected (<i>SP</i> =1). | R | Undefined | | | | | | |

Table 6.51 CacheErr Register Field Descriptions (Secondary Cache) (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| Index | 18:0 | Index. Specifies the cache index of the double word in which the error was detected. The way of the faulty cache is written by hardware in the <i>Way</i> field. Software must combine the <i>Way</i> and <i>Index</i> read in this register with cache configuration information in the <i>Config2</i> register in order to obtain an index which can be used in an indexed CACHE instruction to access the faulty cache data or tag. Note that <i>Index</i> is aligned as a byte index, so it does not need to be shifted by software before it is used in an indexed CACHE instruction. <i>Index</i> bits [4:3] are undefined upon tag RAM errors and <i>Index</i> bits above the MSB actually used for cache indexing will also be undefined. | R | Undefined |

6.2.38 ITagLo Register (CP0 Register 28, Select 0)

The *ITagLo* register acts as the interface to the instruction cache tag array. The Index Store Tag and Index Load Tag operations of the CACHE instruction use the *ITagLo* register as the source of tag information. Note that the 24K core does not implement the *ITagHi* register.

When the *WST* bit of the *ErrCtl* register is asserted, this register becomes the interface to the way-selection RAM. In this mode, the fields are redefined to give appropriate access the contents of the WS array instead of the Tag array. Refer to Figure 8.2 for the layout of the way-selection RAM.

Figure 6.41 ITagLo Register Format (*ErrCtl*_{WST}=0, *ErrCtl*_{SPR}=0)

| | | | | | | | | | | |
|--------|----|----|---|---|---|---|---|---|---|---|
| 31 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 1 | 0 |
| PTagLo | | | | | | | | U | R | P |

Figure 6.42 ITagLo Register Format (*ErrCtl*_{WST}=1, *ErrCtl*_{SPR}=0)

| | | | | | | | | | | | | | |
|--------|----|----|----|----|-------|----|--------|---|---|---|---|---|---|
| 31 | 24 | 23 | 20 | 19 | 15 | 10 | 9 | 8 | 7 | 5 | 4 | 1 | 0 |
| Unused | | | | | WSLRU | R | Unused | | | R | U | | |

Figure 6.43 ITagLo Register Format (*ErrCtl*_{WST}=0, *ErrCtl*_{SPR}=1)

| | | | | | | | | | |
|-----|--------|----|----|------|----|---|---|---|---|
| tag | 31 | 20 | 19 | 12 | 11 | 8 | 7 | 6 | 0 |
| 0 | BasePA | | | | | 0 | E | 0 | |
| 1 | 0 | | | Size | | 0 | | | |

Table 6.52 ITagLo Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|----------|---------|---|--------------|-------------|
| Name | Bit(s) | | | |
| Unused/U | various | Not used in certain modes of operation. | R/W | Undefined |

Table 6.52 ITagLo Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|----------|---|--------------|-------------|
| Name | Bit(s) | | | |
| PTagLo | 31:11 | This field contains the physical address of the cache line. Bit 31 corresponds to bit 31 of the PA and bit 11 corresponds to bit 11 of the PA. Bit 11 is only used when 8KB caches are implemented. For other cache sizes, this bit will not exist in the tag and will be written as a 0 on IndexLoadTag operations. | R/W | Undefined |
| R | 9:8, 4:1 | Must be written as zero; returns zero on read. | 0 | 0 |
| V | 7 | This field indicates whether the cache line is valid. | R/W | Undefined |
| L | 5 | Specifies the lock bit for the cache tag. When this bit is set, and the valid bit is set, the corresponding cache line will not be replaced by the cache replacement algorithm. | R/W | Undefined |
| P | 0 | Parity. Specifies the parity bit for the cache tag. This bit is updated with tag array parity on CACHE Index Load Tag operations and used as tag array parity on Index Store Tag operations when the <i>PO</i> bit of the <i>ErrCtl</i> register is set. | R/W | Undefined |
| WSLRU | 15:10 | LRU bits. This field contains the value read from the WS array after a CACHE Index Load WS operation. It is used to store into the WS array during CACHE Index Store WS operations. | R/W | Undefined |
| BasePA | 31:12 | When reading pseudo-tag 0 of a scratchpad RAM, this field will contain bits [31:12] of the base address of the scratchpad region | R/W | Undefined |
| E | 7 | When reading pseudo-tag 0 of a scratchpad RAM, this bit will indicate whether the scratchpad is enabled | R/W | Undefined |
| Size | 19:12 | When reading pseudo-tag 1 of a scratchpad RAM, this field indicates the size of the scratchpad array. This field is the number of 4KB sections it contains. (Combined with the 0's in 11:0, the register will contain the number of bytes in the scratchpad region.) | R/W | Undefined |

6.2.39 DTagLo Register (CP0 Register 28, Select 2)

The *DTagLo* register acts as the interface to the data cache tag array. The Index Store Tag and Index Load Tag operations of the CACHE instruction use the *DTagLo* register as the source of tag information. Note that the 24K core does not implement the *DTagHi* register.

When the *WST* bit of the *ErrCtl* register is asserted, this register becomes the interface to the way-selection RAM. In this mode, the fields are redefined to give appropriate access the contents of the WS array instead of the Tag array. Refer to Figure 8.2 for the layout of the way-selection RAM.

Figure 6.44 DTagLo Register Format (ErrCtl_{WST}=0, ErrCtl_{SPR}=0)

| | | | | | | | | | | | | |
|--------|----|----|---|---|---|---|---|---|---|---|---|---|
| 31 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| PTagLo | | | | | | | | | | | U | P |

Figure 6.45 DTagLo Register Format (ErrCtl_{WST}=1, ErrCtl_{SPR}=0)

| | | | | | | | | | | | | | | | |
|--------|----|----|----|------|----|-----|---|-------|---|---|---|--------|---|---|---|
| 31 | 24 | 23 | 20 | 19 | 15 | 10 | 9 | 8 | 7 | 5 | 4 | 3 | 2 | 1 | 0 |
| Unused | | | | WSDP | | WSD | | WSLRU | | | R | Unused | | R | U |

Figure 6.46 DTagLo Register Format (ErrCtl_{WST}=0, ErrCtl_{SPR}=1)

| | | | | | | | | | | | |
|-----|--------|------|----|----|----|---|---|---|---|---|---|
| tag | 31 | 20 | 19 | 12 | 11 | 8 | 7 | 6 | 2 | 1 | 0 |
| 0 | BasePA | | | | 0 | E | 0 | U | 0 | | |
| 1 | 0 | Size | | | 0 | | | U | 0 | | |

Table 6.53 DTagLo Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|----------|----------|--|--------------|-------------|
| Name | Bit(s) | | | |
| Unused/U | various | Not used in certain modes of operation. | R/W | Undefined |
| PtagLo | 31:11 | This field contains the physical address of the cache line. Bit 31 corresponds to bit 31 of the PA and bit 11 corresponds to bit 11 of the PA. Bit 11 is only used when 8KB caches are implemented. For other cache sizes, this bit will not exist in the tag and will be written as a 0 on IndexLoadTag operations. | R/W | Undefined |
| R | 9:8, 4:1 | Must be written as zero; returns zero on read. | 0 | 0 |
| V | 7 | This field indicates whether the cache line is valid. | R/W | Undefined |
| D | 6 | This field indicates whether the cache line is dirty. It will only be set if bit 7 (valid) is also set. For L1 I-cache, this field must be written as zero and returns zero on read. | R/W | Undefined |
| L | 5 | Specifies the lock bit for the cache tag. When this bit is set, and the valid bit is set, the corresponding cache line will not be replaced by the cache replacement algorithm. | R/W | Undefined |
| P | 0 | Parity. Specifies the parity bit for the cache tag. This bit is updated with tag array parity on CACHE Index Load Tag operations and used as tag array parity on Index Store Tag operations when the <i>PO</i> bit of the <i>ErrCtl</i> register is set. This parity does not cover the dirty bit; the dirty bit has a separate parity bit placed in the way selection RAM. | R/W | Undefined |
| WSDP | 23:20 | Dirty Parity (Optional). This field contains the value read from the WS array during a CACHE Index Load WS operation. If the <i>PO</i> field of the <i>ErrCtl</i> register is asserted, then this field is used to store the dirty parity bits during a CACHE Index Store WS operation. | R/W | Undefined |
| WSD | 19:16 | Dirty bits. This field contains the value read from the WS array after a CACHE Index Load WS operation. It is used to store into the WS array during CACHE Index Store WS operations. | R/W | Undefined |
| WSLRU | 15:10 | LRU bits. This field contains the value read from the WS array after a CACHE Index Load WS operation. It is used to store into the WS array during CACHE Index Store WS operations. | R/W | Undefined |
| BasePA | 31:12 | When reading pseudo-tag 0 of a scratchpad RAM, this field will contain bits [31:12] of the base address of the scratchpad region | R/W | Undefined |
| E | 7 | When reading pseudo-tag 0 of a scratchpad RAM, this bit will indicate whether the scratchpad is enabled | R/W | Undefined |
| Size | 19:12 | When reading pseudo-tag 1 of a scratchpad RAM, this field indicates the size of the scratchpad array. This field is the number of 4KB sections it contains. (Combined with the 0's in 11:0, the register will contain the number of bytes in the scratchpad region.) | R/W | Undefined |

In addition to the three uses of the *DTagLo* register specified above, there is a fourth application where *DTagLo* is used to access the pseudo-tags (control registers) of the ITC block. This is done by executing the Index Store Tag or Index Load Tag operation of the CACHE instruction with the *ErrCtlITC* set to 1 (and *ErrCtlSPR/ErrCtlWST* set to 0).

6.2.40 L23TagLo Register (CP0 Register 28, Select 4)

The *L23TagLo* register acts as the interface to the L2 or L3 cache tag array. The Index Store Tag and Index Load Tag operations of the CACHE instruction use the *L23TagLo* register as the source of tag information. Note that the 24K core does not implement the *L23TagHi* register.

The definition of this register is dependent on the L2/L3 implementation. The core implements this as a general 32b R/W register.

6.2.41 IDataLo Register (CP0 Register 28, Select 1)

The *IDataLo* register is a register that acts as the interface to the instruction cache data array and is intended for diagnostic operations only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *IDataLo* register. If the *WST* bit in the *ErrCtl* register is set, then the contents of *IDataLo* can be written to the cache data array by doing an Index Store Data CACHE instruction. If the *SPR* bit in the *ErrCtl* register is set, then the contents of *IDataLo* can be written to the scratchpad RAM data array by doing an Index Store Data CACHE instruction.

Figure 6.47 IDataLo Register Format



Table 6.54 IDataLo Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| DATA | 31:0 | Low-order data read from the cache data array. | R/W | Undefined |

6.2.42 DDataLo Register (CP0 Register 28, Select 3)

The *DDataLo* register is a register that acts as the interface to the data cache data array and is intended for diagnostic operations only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *DDataLo* register. If the *WST* bit in the *ErrCtl* register is set, then the contents of *DDataLo* can be written to the cache data array by doing an Index Store Data CACHE instruction. If the *SPR* bit in the *ErrCtl* register is set, then the contents of *DDataLo* can be written to the scratchpad RAM data array by doing an Index Store Data CACHE instruction.

Figure 6.48 DDataLo Register Format

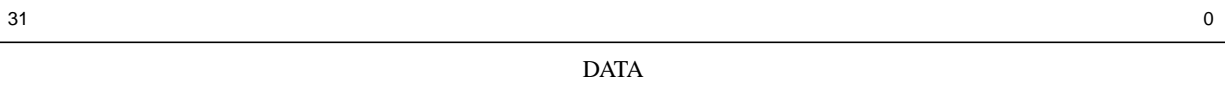


Table 6.55 DDataLo Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| DATA | 31:0 | Low-order data read from the cache data array. | R/W | Undefined |

6.2.43 L23DataLo Register (CP0 Register 28, Select 5)

The *L23DataLo* register is a register that acts as the interface to the L2 or L3 cache data array and is intended for diagnostic operations only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *L23DataLo* register. If the *WST* bit in the *ErrCtl* register is set, then the contents of *L23DataLo* can be written to the cache data array by doing an Index Store Data CACHE instruction. If the *SPR* bit in the *ErrCtl* register is set, then the contents of *L23DataLo* can be written to the scratchpad RAM data array by doing an Index Store Data CACHE instruction.

Figure 6.49 L23DataLo Register Format



Table 6.56 L23DataLo Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| DATA | 31:0 | Low-order data read from the cache data array. | R/W | Undefined |

6.2.44 IDataHi Register (CP0 Register 29, Select 1)

The *IDataHi* register is a register that acts as the interface to the cache data array and is intended for diagnostic operations only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *IDataHi* register. If the *WST* bit in the *ErrCtl* register is set, then the contents of *IDataHi* can be written to the cache data array by doing an Index Store Data CACHE instruction. If the *SPR* bit in the *ErrCtl* register is set, then the contents of *IDataHi* can be written to the scratchpad RAM data array by doing an Index Store Data CACHE instruction.

The interface to the I-cache only operates on pairs of instructions - the high instruction will be written into the *IDataHi* register. Note that *IDataHi* and *IDataLo* reflect the memory ordering of the instructions. Depending on the endianness of the system, Instruction0 belongs in either *IDataHi* (BigEndian) or *IDataLo* (LittleEndian) and vice versa for Instruction1.

Figure 6.50 IDataHi Register Format



Table 6.57 IDataHi Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| DATA | 31:0 | High-order data read from the cache data array. | R/W | Undefined |

6.2.45 L23DataHi Register (CP0 Register 29, Select 5)

The *L23DataHi* register is a register that acts as the interface to the cache data array and is intended for diagnostic operations only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *L23DataHi* register. If the *WST* bit in the *ErrCtl* register is set, then the contents of *L23DataHi* can be written to the cache data array by doing an Index Store Data CACHE instruction.

Figure 6.51 L23DataHi Register Format



Table 6.58 L23DataHi Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| DATA | 31:0 | High-order data read from the cache data array. | R/W | Undefined |

6.2.46 ErrorEPC (CP0 Register 30, Select 0)

The *ErrorEPC* register is a read/write register, similar to the *EPC* register, except that *ErrorEPC* is used on error exceptions. All bits of the *ErrorEPC* register are significant and must be writable. It is also used to store the program counter on Reset, Soft Reset, and nonmaskable interrupt (NMI) exceptions.

The *ErrorEPC* register contains the virtual address at which instruction processing can resume after servicing an error. This address can be:

- The virtual address of the instruction that caused the exception, or
- the virtual address of the immediately preceding branch or jump instruction when the error causing instruction is in a branch delay slot.

Unlike the *EPC* register, there is no corresponding branch delay slot indication for the *ErrorEPC* register.

In processors that implement the MIPS16 ASE, a read of the *ErrorEPC* register (via MFC0) returns the following value in the destination GPR:

$$\text{GPR}[\text{rt}] \leftarrow \text{ErrorExceptionPC}_{31..1} \parallel \text{ISAMode}_0$$

That is, the upper 31 bits of the error exception PC are combined with the lower bit of the *ISAMode* field and written to the GPR.

Similarly, a write to the *ErrorEPC* register (via MTC0) takes the value from the GPR and distributes that value to the error exception PC and the *ISAMode* field, as follows

$$\begin{aligned} \text{ErrprExceptionPC} &\leftarrow \text{GPR}[\text{rt}]_{31..1} \parallel 0 \\ \text{ISAMode} &\leftarrow 2\#0 \parallel \text{GPR}[\text{rt}]_0 \end{aligned}$$

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the error exception PC, and the lower bit of the error exception PC is cleared. The upper bit of the *ISAMode* field is cleared and the lower bit is loaded from the lower bit of the GPR.

Figure 6.52 ErrorEPC Register Format



Table 6.59 ErrorEPC Register Field Description

| Fields | | Description | Read / Write | Reset State |
|----------|--------|----------------------------------|--------------|-------------|
| Name | Bit(s) | | | |
| ErrorEPC | 31:0 | Error Exception Program Counter. | R/W | Undefined |

6.2.47 DeSave Register (CP0 Register 31, Select 0)

The Debug Exception Save (*DeSave*) register is a read/write register that functions as a simple memory location. This register is used by the debug exception handler to save one of the GPRs, which is then used to save the rest of the context to a pre-determined memory area (such as in the EJTAG Probe). This register allows the safe debugging of exception handlers and other types of code where the existence of a valid stack for context saving cannot be assumed.

Figure 6.53 DeSave Register Format



Table 6.60 DeSave Register Field Description

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--------------------------------|--------------|-------------|
| Name | Bit(s) | | | |
| DESAVE | 31:0 | Debug exception save contents. | R/W | Undefined |

Hardware and Software Initialization of the 24K® Core

A 24K processor core contains only a minimal amount of hardware initialization and relies on software to fully initialize the device.

This chapter contains the following sections:

- [Section 7.1 “Hardware-Initialized Processor State”](#)
- [Section 7.2 “Software Initialized Processor State”](#)

7.1 Hardware-Initialized Processor State

A 24K processor core, like most other MIPS processors, is not fully initialized by hardware reset. Only a minimal subset of the processor state is cleared. This is enough to bring the core up while running in unmapped and uncached code space. All other processor state can then be initialized by software. Unlike previous MIPS processors, there is no distinction between cold and warm resets (or hard and soft resets). *SL_Reset* is used for both power-up reset and soft reset.

7.1.1 Coprocessor 0 State

Much of the hardware initialization occurs in Coprocessor 0.

- *Random* - cleared to maximum value on Reset (TLB MMU only)
- *Wired* - cleared to 0 on Reset (TLB MMU only)
- *Status_BEV* - set to 1 on Reset
- *Status_TS* - cleared to 0 on Reset
- *Status_NMI* - cleared to 0 on Reset
- *Status_ERL* - set to 1 on Reset
- *Status_RP* - cleared to 0 on Reset
- *WatchLo_{I,R,W}* - cleared to 0 on Reset
- *Config* fields related to static inputs - set to input value by Reset
- *Config_K0* - set to 010 (uncached) on Reset
- *Config_KU* - set to 010 (uncached) on Reset (FM MMU only)

- *Config_{K23}* - set to 010 (uncached) on Reset (FM MMU only)
- *Debug_{DM}* - cleared to 0 on Reset (unless EJTAGBOOT option is used to boot into DebugMode, see [Chapter 11](#), “EJTAG Debug Support in the 24K® Core” on page 240 for details)
- *Debug_{LSNM}* - cleared to 0 on Reset
- *Debug_{IBusEP}* - cleared to 0 on Reset
- *Debug_{DBusEP}* - cleared to 0 on Reset
- *Debug_{IEXI}* - cleared to 0 on Reset
- *Debug_{SSi}* - cleared to 0 on Reset

7.1.2 TLB Initialization

Each TLB entry has a “hidden” state bit, which is set by Reset and is cleared when the TLB entry is written. This bit disables matches and prevents “TLB Shutdown” conditions from being generated by the power-up values in the TLB array (when two or more TLB entries match on a single address). This bit is not visible to software.

7.1.3 Bus State Machines

When a Reset exception is taken, all pending bus transactions are aborted, and the state machines in the bus interface unit are reset.

7.1.4 Static Configuration Inputs

All static configuration inputs (for example, defining the bus mode and cache size) should only be changed during Reset.

7.1.5 Fetch Address

By default, the fetch is directed to VA 0xBFC00000 (PA 0x1FC00000) upon Reset. This address is in kseg1, which is unmapped and uncached, so that the TLB and caches do not require hardware initialization.

This initial fetch address can be overridden via core inputs. See [Section 5.5 “Exception Vector Locations”](#) for additional details.

If EJTAGBOOT is active (see [Section 11.3.3.8 “EJTAGBOOT Instruction”](#)), the processor will begin fetching instructions directly from the EJTAG probe rather than from memory.

7.2 Software Initialized Processor State

Software is required to initialize the following parts of the device.

7.2.1 Register File

The register file powers up in an unknown state with the exception of r0 which is always 0. Initializing the rest of the register file is not required for proper operation. Good code will generally not read a register before writing to it, but the boot code can initialize the register file for added safety.

7.2.2 TLB

Because of the hidden bit indicating initialization, the core does not initialize the TLB upon Reset. This is an implementation specific feature of the 24K core and cannot be relied upon if writing generic code for MIPS32/64 processors.

7.2.3 Caches

The cache tag and data arrays power up to an unknown state and are not affected by reset. Every tag in the cache arrays should be initialized to an invalid state using the CACHE instruction (typically the Index Invalidate function). This can be a long process, especially since the instruction cache initialization needs to be run in an uncached address region.

7.2.4 Coprocessor 0 State

Miscellaneous COP0 states need to be initialized prior to leaving the boot code. There are various exceptions which are blocked by *ERL*=1 or *EXL*=1 and which are not cleared by Reset. These can be cleared to avoid taking spurious exceptions when leaving the boot code.

- *Cause*: *WP* (Watch Pending), *SW0/1* (Software Interrupts) should be cleared.
- *Config*: *K0* (kseg0 Coherency Algorithm) should be set to the desired Cache Coherency Algorithm (CCA) prior to accessing kseg0.
- *Config*: (FM MMU only) *KU* and *K23* should be set to the desired CCA for USeg/KUSeg and kseg2/3 respectively prior to accessing those regions.
- *Count*: Should be set to a known value if Timer Interrupts are used.
- *Compare*: Should be set to a known value if Timer Interrupts are used. The write to compare will also clear any pending Timer Interrupts (and thus, *Count* should be set before *Compare*, to avoid any unexpected interrupts).
- *Status*: Desired state of the device should be set.
- Other COP0 state: Other registers should be written before they are read. Some registers are not explicitly writeable, and are only updated as a by-product of instruction execution or a taken exception. Uninitialized bits should be masked off after reading these registers.

Caches of the 24K® Core

This chapter describes the caches present in a 24K processor core. It contains the following sections:

- [Section 8.1 “Cache Configurations”](#)
- [Section 8.2 “Instruction Cache”](#)
- [Section 8.3 “Data Cache”](#)
- [Section 8.4 “Write Back Buffer”](#)
- [Section 8.5 “Cache Protocols”](#)
- [Section 8.6 “CACHE Instruction”](#)
- [Section 8.7 “Software Cache Testing”](#)
- [Section 8.8 “Memory Coherence Issues”](#)

8.1 Cache Configurations

A 24K processor core has separate instruction and data caches which allows instruction and data references to proceed simultaneously. Each of the caches is 4-way set associative and they can be independently configured at build time to be 8, 16, 32, or 64KB. Both caches use a 32B line size and support locking on a per line basis. Parity protection of the cache arrays is an optional feature.

8.2 Instruction Cache

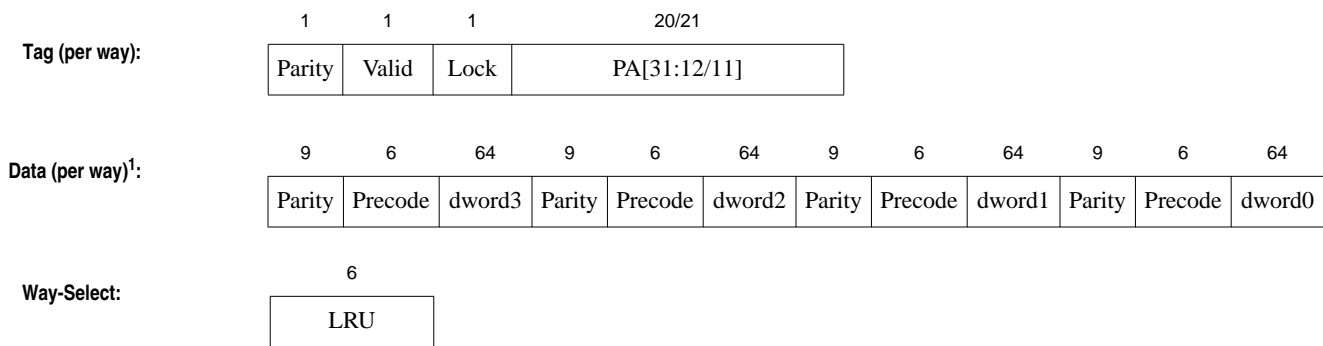
[Table 8.1](#) shows the key characteristics of the instruction cache. [Figure 8.1](#) shows the format of an entry in the three arrays comprising the instruction cache: tag, data, and way-select. Note that for 8KB caches, there is one extra tag bit needed.

Table 8.1 Instruction Cache Attributes

| Attribute | With Parity | Without Parity |
|----------------------|--------------------|----------------|
| Size | 0, 8, 16, 32, 64KB | |
| Line Size | 32B | |
| Number of Cache Sets | 64, 128, 256, 512 | |
| Associativity | 4 way | |
| Replacement | LRU | |
| Cache Locking | per line | |

Table 8.1 Instruction Cache Attributes

| Attribute | With Parity | Without Parity |
|----------------------|-------------|----------------|
| Data Array | | |
| Read Unit | 79b x 4 | 70b x 4 |
| Write Unit | 79b | 70b |
| Tag Array | | |
| Read Unit (8KB) | 24b x 4 | 23b x 4 |
| Read Unit (non-8KB) | 23b x 4 | 22b x 4 |
| Write Unit (8KB) | 24b | 23b |
| Write Unit (non-8KB) | 23b | 22b |
| Way-Select Array | | |
| Read Unit | 6b | |
| Write Unit | 1-6b | |

Figure 8.1 Instruction Cache Organization

1. Parity Bits in data array will be interleaved with precode and data bytes

8.2.1 Virtual Aliasing

The instruction cache on the 24K processor core is virtually indexed and physically tagged. The lower bits of the virtual address are used to access the cache arrays and the physical address is used in the tags. Because the way size can be larger than the minimum TLB page size, there is a potential for virtual aliasing. This means that one physical address can exist in multiple indices within the cache if it is accessed with different virtual addresses.

This reduces the cache efficiency somewhat, but is generally not a problem unless the instruction stream is being written to. When instructions are written, software must ensure that the store data is written out to memory and the old data is invalidated in the instruction cache (via the CACHE or SYNCI instruction). For this to work correctly, the address must be invalidated from each of the possible alias locations. The 24K processor includes a feature to simplify this task and automatically invalidate the physical address from all of the alias locations. The presence of this feature and the enable for it are located in the *Config7* register. *Config7*_{AR}=1 indicates that aliases are possible (cache > 16KB and TLB-based MMU) and this feature is present. This feature is enabled by default, but *Config7*_{VA} can be set to 1 to disable it. Looking up the other alias locations does slow down the invalidate slightly, so software can disable it when aliases are known not to be present, for example, when using an OS with 16KB TLB pages,

8.2.2 Precode Bits

In order for the fetch unit to quickly detect branches and jumps when executing code, the instruction cache array contains some additional precode bits. These bits indicate the type and location of branch or jump instructions within a 64b fetch bundle. These precode bits are not used when executing MIPS16e code.

8.2.3 Parity

Parity protection of the instruction cache arrays can optionally be included. The data array has a 9 parity bits - one for the 6 precode bits and one for each byte of the 64b data. The tag array has a single parity bit for each tag. The LRU array does not have any parity.

8.3 Data Cache

The data cache is similar to the instruction cache, with a few key differences:

- The data cache does not contain any precode information.
- To handle store bytes, the data array is byte accessible and the optional data parity is 1 bit per byte.
- The way-select array for the data cache also holds the dirty bits (and optional dirty parity bits) for each cache line, in addition to the LRU information.
- Virtual aliases must be handled differently

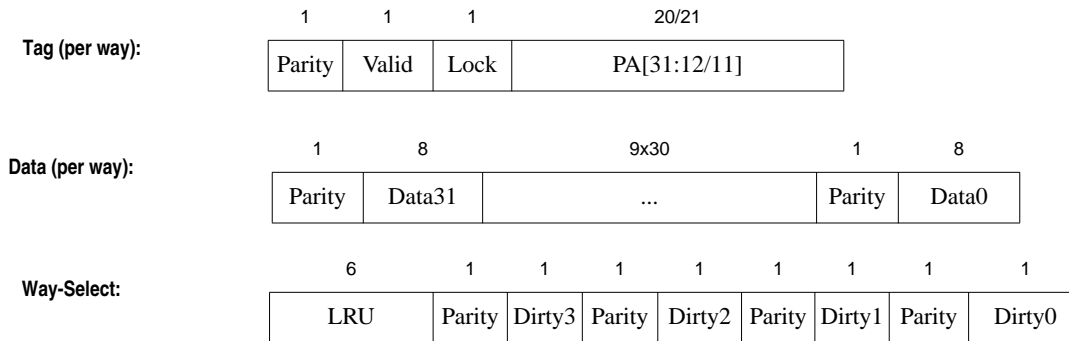
Table 8.2 shows the key characteristics of the data cache. Figure 8.2 shows the format of an entry in the three arrays comprising the data cache: tag, data, and way-select.

Table 8.2 Data Cache Attributes

| Attribute | With Parity | Without Parity |
|----------------------|--------------------|----------------|
| Size | 0, 8, 16, 32, 64KB | |
| Line Size | 32B | |
| Number of Cache Sets | 64, 128, 256, 512 | |
| Associativity | 4 way | |
| Replacement | LRU | |
| Cache Locking | per line | |
| Data Array | | |
| Read Unit | 72b x 4 | 64b x 4 |
| Write Unit | 9b | 8b |
| Tag Array | | |
| Read Unit (8KB) | 24b x 4 | 23b x 4 |
| Read Unit (non-8KB) | 23b x 4 | 22b x 4 |
| Write Unit (8KB) | 24b | 23b |
| Write Unit (non-8KB) | 23b | 22b |
| Way-Select Array | | |

Table 8.2 Data Cache Attributes (Continued)

| Attribute | With Parity | Without Parity |
|------------|-------------|----------------|
| Read Unit | 14b | 10b |
| Write Unit | 1-14b | |

Figure 8.2 Data Cache Organization

8.3.1 Virtual Aliasing

Since the data cache is virtually indexed and physically tagged, a potential issue referred to as *virtual aliasing* might exist. Virtual aliasing occurs if the virtual bits used to index a cache array are not consistent with the overlapping physical bits, after the virtual address has been translated to a physical address. The possibility of virtual aliasing only occurs in address regions which are mapped through a TLB-based memory management unit.

In TLB-mapped address regions, virtual aliasing may occur if the cache size per way is greater than the page size. For example, consider a 32KB cache organized as 4-way set associative. The size per way is then 8 KB, so virtual address bits [12:0] are used to index the array. If the address is in a translated region with a page size of 4 KB, then address bits [11:0] are untranslated but address bits [31:12] will be mapped and for these bits the virtual and physical addresses may be different. In this example, bit [12] could pose a potential problem due to virtual aliasing. Imagine two virtual addresses, VA0 and VA1, whose only difference is the value of bit [12], which map to the same physical address. These two virtual addresses would be indexed to two different lines by the cache, even though they were intended to represent the same physical address. Then if a program does a load using VA0 and a store using VA1, or vice-versa, the cache may not return the expected data.

Table 8.3 shows the overlapped virtual/physical address bits which could potentially be involved in virtual aliasing, given the possible minimum page sizes and cache way sizes supported by a 24K core. Virtual aliasing is generally only a problem for the D-cache, since stores don't happen to the I-cache. A special hardware mechanism is available to prevent the possibility of virtual aliasing in 32KB and 64KB data caches. In cores not configured with this mechanism, virtual aliasing must be handled by software. The software solution must ensure that the mapping of virtual

address bits which overlap with physical address bits be handled consistently. The simplest approach is to ensure that the overlapping bits are unity-mapped (VA equals PA).

Table 8.3 Potential Virtual Aliasing Bits

| Minimum Page Size (KB) | Cache Way Size (KB) | Overlapped address bits with possible aliasing |
|------------------------|---------------------|--|
| 4 | 8 | [12] |
| | 16 | [13:12] |
| 8 | 16 | [13] |

A related issue can occur in virtually indexed, physically tagged caches if the number of physical bits stored in the tag array does not fully overlap the physically translated bits for the smallest page size. For a 24K core, there are always at least 20 address bits stored in the cache tag, representing bits [31:12] of the physical address. Since the minimum page size is 4KB with bits [31:12] physically translated by the TLB, the cache tag size does overlap the translated bits and this issue will not occur.

8.3.2 Parity

Parity protection of the data cache arrays can optionally be included. The data array requires a parity bit for each byte, to correspond to the minimum write quantum for a store. The tag array has a single parity bit for each tag. The way-select array has separate parity bits to cover each dirty bit, but the LRU bits are not covered by parity.

8.4 Write Back Buffer

The BIU includes a Write Back Buffer (WBB) that holds writes going to memory. This includes evictions from the data cache, as well as write-through stores, uncached stores, and uncached accelerated stores. The WBB consists of 4 entries, each of which is capable of holding 32B of data. The WBB also holds L2 CACHE instructions that are to be sent out on the bus.

The WBB will attempt to gather uncached accelerated (UCA) stores to allow full line burst writes. UCA behavior is described in [Section 8.4.1 “Uncached Accelerated Stores”](#). Write through stores can also be gathered in a WBB entry if *ConfigMM* = 1.

WBB entries are ‘flushed’ under a variety of conditions. When a buffer is flushed, the write command is queued in the BIU and the WBB entry will not accept any more activity until the data has been written to the bus and the buffer is freed up. UCA flush conditions are described in the next section. Flush conditions for other types are shown here:

- Uncached (non-accelerated) stores flush immediately
- L2 CACHE instruction commands are also flushed immediately
- Entries for D\$ evictions are flushed when all 4 dwords (32B) of data have been gathered
- Write-through entries are flushed under the following conditions:
 - A full 32B line has been gathered
 - A read request matches the address of the WT line. The write command will be ordered ahead of the read command. There is no direct bypass of the WBB data to the read—the read gets the data from memory.

- A WT request to a different 32B line is seen. Only 1 WT merge can be active at any time.

8.4.1 Uncached Accelerated Stores

Uncached Accelerated gathering is supported for word and double word stores only.

Gathering of uncached accelerated stores will start on cache-line aligned addresses, i.e. 32 byte aligned addresses. Uncached accelerated word or double word stores that do not meet that condition will be treated like regular uncached stores.

An uncached accelerated store to the start of a new line will reserve a write-back buffer entry for gathering. Subsequent uncached accelerated word or double word stores to the same cache line will write sequentially into this buffer, independent of the word address associated with these stores. The uncached accelerated buffer is tagged with the address of the first store.

An uncached accelerated buffer is written to memory (flushed) if:

1. The last word in the entry being gathered is written. (Implicit flush)
2. A PREF Nudge which match the address associated with the gather buffer (Explicit flush).
3. A SYNC instruction is executed. (Explicit flush)
4. Bits <31:5> of the address of a Load instruction match the address associated with the gather buffer. (Implicit flush)
5. Uncached Accelerated store to a different 32B line (Implicit flush)
6. An exception occurs. (Implicit flush)

When an uncached accelerated buffer is flushed, the address sent out on the system interface is the address associated with the gather buffer.

Caveats:

- Uncached Accelerated stores are not ordered with respect to uncached accesses. Any uncached stores and any uncached loads to unrelated addresses that occur between uncached accelerated stores that are part of a gather sequence may occur out of order.
- The only constraint imposed on the gathering is that doubleword stores are only allowed to write to double word aligned locations in the buffer. For example if uncached accelerated gathering starts with a Store Word (SW), it may not immediately be followed by a Store Double (SDC1).
- Uncached accelerated stores of the following types are not intended to be used by software and may generate unpredictable results:
 1. Sub-word (byte, halfword, tri-byte) Stores
 2. Unaligned Stores
 3. Store conditionals

- In order for software to be able to run functionally correct on implementations without uncached accelerated stores, software should always generate accesses starting on a cache-line aligned address, proceed to generate correctly incremented sequential addresses and observe the restrictions for uncached accelerated stores.

8.5 Cache Protocols

This section describes cache organization, attributes, and cache-line replacement for the instruction and data caches. This section also discusses issues relating to virtual aliasing.

8.5.1 Cache Organization

The instruction and data caches each consist of three arrays: tag, data and way-select. The caches are virtually indexed, since a virtual address is used to select the appropriate line within each of the three arrays. The caches are physically tagged, as the tag array contains a physical, not virtual, address.

The tag and data arrays hold 4 ways of information per set, corresponding to the 4-way set associativity of the cache. The way-select array holds information to choose the way to be filled, as well as dirty bits in the case of the data cache.

Figure 8.1 (instruction cache) and Figure 8.2 (data cache) show the format of each line in the tag, data and way-select arrays.

A tag entry consists of the upper 20 or 21 bits of the physical address (bits [31:12/11]) (bit 11 is only used for 8KB caches), one valid bit for the line, and a lock bit. A data entry contains the four 64-bit doublewords in the line, for a total of 32 bytes. All four words in the line are present or not in the data array together, hence the single valid bit stored with the tag. Once a valid line is resident in the cache, byte, halfword, triple-byte or full word stores can update all or a portion of the words in that line. The tag and data entries are repeated for each of the 4 lines in the set.

A way-select entry holds bits choosing the way to be replaced according to a Least Recently Used (LRU) algorithm. The LRU information applies to all the ways and there is one way-select entry for all the ways in the set. The array with way-select entries for the data cache also holds dirty bits for the lines. One dirty bit is required per line, as shown in Figure 8.2. The instruction cache only supports reads, hence only LRU entries are stored in the instruction way-select array.

8.5.2 Cacheability Attributes

A 24K core supports the following cacheability attributes:

- *Uncached:* Addresses in a memory area indicated as uncached are not read from the cache. Stores to such addresses are written directly to main memory, without changing cache contents.
- *Write-back with write allocation:* Loads and instruction fetches first search the cache, reading main memory only if the desired data does not reside in the cache. On data store operations, the cache is first searched to see if the target address is cache resident. If it is resident, the cache contents are updated, but main memory is not written. If the cache lookup misses on a store, main memory is read to bring the line into the cache and merge it with the new store data. Hence, the allocation policy on a cache miss is read- or write-allocate. Data stores will update the appropriate dirty bit in the way-select array to indicate that the line contains modified data. When a line with dirty data is displaced from the cache, it is written back to memory.
- *Write-through with no write allocation:* Loads and instruction fetches first search the cache, reading main memory only if the desired data does not reside in the cache. On data store operations, the cache is first searched to

see if the target address is cache resident. If it is resident, the cache contents are updated, and main memory is also written. If the cache lookup misses on a store, only main memory is written. Hence, the allocation policy on a cache miss is read-allocate only.

NOTE: The instruction cache always uses a writeback CCA for its bus requests even when the TLB page is mapped as write-through.

- *Uncached Accelerated: Uncached stores are gathered together for more efficient bus utilization. See [Section 8.4.1 “Uncached Accelerated Stores”](#) for more details*

Some segments of memory employ a fixed caching policy; for example kseg1 is always uncacheable. Other segments of memory allow the caching policy to be selected by software. Generally, the cache policy for these programmable regions is defined by a cacheability attribute field associated with that region of memory. See [Chapter 4, “Memory Management of the 24K® Core”](#) on page 87 for further details.

8.5.3 Replacement Policy

The replacement policy refers to how a way is chosen to hold an incoming cache line on a miss which will result in a cache fill. The replacement policy is least recently used (LRU), but excluding any locked ways. The LRU bit(s) in the way-select array encode the order in which ways on that line have been accessed.

On a cache miss, the lock and LRU bits for the tag and way-select entries of the selected line may be used to determine the way which will be chosen.

The LRU field in the way select array is updated as follows:

- On a cache hit, the associated way is updated to be the most recently used. The order of the other ways relative to each another is unchanged.
- On a cache refill, the filled way is updated to be the most recently used.
- On CACHE instructions, the update of the LRU bits depends on the type of operation to be performed:
 - **Index (Writeback) Invalidate:** Least-recently used.
 - **Index Load Tag:** No update.
 - **Index Store Tag, WST=0:** Most-recently used if valid bit is set in *TagLo* CP0 register. Least-recently used if valid bit is cleared in *TagLo* CP0 register.
 - **Index Store Tag, WST=1:** Update the field with the contents of the *TagLo* CP0 register (refer to Table 8.4 for the valid values of this field).
 - **Index Store Data:** No update.
 - **Hit Invalidate:** Least-recently used if a hit is generated, otherwise unchanged.
 - **Fill:** Most-recently used.
 - **Hit (Writeback) Invalidate:** Least-recently used if a hit is generated, otherwise unchanged.
 - **Hit Writeback:** No update.
 - **Fetch and Lock:** For instruction cache, no update. For data cache, most-recently used.

If all ways are valid, then any locked ways will be excluded from consideration for replacement. For the unlocked ways, the LRU bits are used to identify the way which has been used least recently, and that way is selected for replacement.

If the way selected for replacement has its dirty bit asserted in the way-select array, then that 32-byte line will be written back to memory before the new fill can occur.

8.5.4 Line Locking

- The 24K core supports line locking in both caches. A line can be locked by either Fetch and Lock or Index Store Tag CACHE instructions. The core does not support the locking of all 4 ways of either cache at a particular index. If all 4 ways of the cache at a given index are locked, subsequent cache misses at that cache index will displace one of the locked lines.

8.6 CACHE Instruction

Both caches support the CACHE instructions, which allow users to manipulate the contents of the Data and Tag arrays, including the locking of individual cache lines. These instructions are described in detail in [Chapter 12, “24K® Processor Core Instructions”](#) on page 303.

The CACHE Index Load Tag and Index Store Tag instructions can be used to read and write the WS- RAM by setting the *WST* bit in the *ErrCtl* register. (The *ErrCtl* register is described in [Section 6.2.36 “ErrCtl Register \(CP0 Register 26, Select 0\)”](#).) Similarly, the *SPR* bit in the *ErrCtl* register will cause Index Load Tag and Index Store Tag instructions to access the pseudo-tags associated with the scratchpad RAM array. Note that when the *WST* and *SPR* bits are zero, the CACHE index instructions access the cache Tag array.

Not all values of the WS field are valid for defining the order in which the ways are selected. This is only an issue, however, if the WS-RAM is written after the initialization (invalidation) of the Tag array. Valid WS field encodings for way selection order is shown in Table 8.4.

Table 8.4 Way Selection Encoding, 4 Ways

| Selection Order ¹ | WS[5:0] | Selection Order | WS[5:0] |
|------------------------------|---------|-----------------|---------|
| 0123 | 000000 | 2013 | 100010 |
| 0132 | 000001 | 2031 | 110010 |
| 0213 | 000010 | 2103 | 100110 |
| 0231 | 010010 | 2130 | 101110 |
| 0312 | 010001 | 2301 | 111010 |
| 0321 | 010011 | 2310 | 111110 |
| 1023 | 000100 | 3012 | 011001 |
| 1032 | 000101 | 3021 | 011011 |
| 1203 | 100100 | 3102 | 011101 |
| 1230 | 101100 | 3120 | 111101 |
| 1302 | 001101 | 3201 | 111011 |
| 1320 | 101101 | 3210 | 111111 |

1. The order is indicated by listing the least-recently used way to the left and the most-recently used way to the right, etc.

8.7 Software Cache Testing

Typically, the cache RAM arrays will be tested using BIST. It is, however, possible for software running on the processor to test all of the arrays. Of course, testing of the I-cache arrays should be done from an uncacheable space with interrupts disabled in order to maintain the cache contents. There are multiple methods for testing these arrays in software, only one is presented here.

8.7.1 I-Cache and D-cache Tag Arrays

These arrays can be tested via the Index Load Tag and Index Store Tag varieties of the CACHE instruction. Index Store Tag will write the contents of the *TagLo* register into the selected tag entry. Index Load Tag will read the selected tag entry into the *TagLo*.

If parity is implemented, the parity bits can be tested as a normal bit by setting the *PO* bit in the *ErrCtl* register. This will override the parity calculation and write *P* bit in *TagLo* as the parity value.

8.7.2 I-Cache Data Array

This array can be tested using the Index Store Data and Index Load Tag varieties of the CACHE instruction. The Index Store Data variety is enabled by setting the *WST* bit in the *ErrCtl* register.

The precode bits in the array can be tested by setting the *PCO* bit in the *ErrCtl* register. This will write the *PCI* field in the *ErrCtl* register instead of calculating the precode bits on a write.

The parity bits in the array can be tested by setting the *PO* bit in the *ErrCtl* register. This will use the *PI* field in *ErrCtl* instead of calculating the parity on a write.

The rest of the data bits are read/written to/from the *DataLo* and *DataHi* registers.

8.7.3 I-Cache WS Array

The testing of this array is done with via Index Load Tag and Index Store Tag CACHE instructions. By setting the *WST* bit in the *ErrCtl* register, these operations will read and write the WS array instead of the tag array.

8.7.4 D-Cache Data Array

This array can be tested using the Index Store Tag CACHE, SW, and LW instructions. First, use Index Store Tag to set the initial state of the tags to valid with a known physical address (PA). Write the array using SW instructions to the PAs that are resident in the cache. The value can then be read using LW instructions and compared to the expected data.

The parity bits can be implicitly tested using this mechanism. The parity bits can be explicitly tested by setting the *PO* bit in *ErrCtl* and using Index Store Data and Index Load Tag CACHE operations. The parity bits (one bit per byte) are read/written to/from the *PD* field in *ErrCtl*. Unlike the I-cache, the *DataHi* register is not used and only 32b of data is read/written per operation.

8.7.5 D-cache WS Array

The dirty bits in this array will be tested when the data tag is tested. The LRU bits can be tested using the same mechanism as the I-cache WS array.

8.8 Memory Coherence Issues

A cache presents coherency issues within the memory hierarchy which must be considered in the system design. Since a cache holds a copy of memory data, it is possible for another memory master to modify a memory location, thus making other copies of that location stale if those copies are still in use. A detailed discussion of memory coherence is beyond the scope of this document, but following are a few related comments.

A24K processor contains no direct hardware support for managing coherency with respect to its caches, so it must be handled via system design or software. The data cache supports either write-back or write-through protocols.

In write-through mode, all data writes will eventually be sent to memory. Due to write buffers, however, there could be a delay in how long it takes for the write to memory to actually occur. If another memory master updates cacheable memory which could also be in the cores caches, then those locations may need to be flushed from the cache. The only way to accomplish this invalidation is by use of the CACHE instruction.

In write-back mode, data writes only go to the cache and not to memory. So the processor cache may contain the *only* copy of data in the system until that data is written to main memory. Dirty lines are only written to memory when displaced from the cache as a new line is filled or if explicitly forced by certain flavors of the CACHE or PREF instructions.

The SYNC instruction may also be useful to software enforcing memory coherence, as it flushes the core's write buffers.

Power Management in the 24K® Core

A 24K processor core offers a number of power management features, including low-power design, active power management and power-down modes of operation. The core is a static design that supports changing the clock frequency or even stopping the clocks to manage power. The WAIT instruction suspends execution until an interrupt is detected and can put the core into a low power mode.

The core provides two basic mechanisms for system level low-power support discussed in the following sections.

- [Section 9.1 “Register-Controlled Power Management”](#)
- [Section 9.2 “Instruction-Controlled Power Management”](#)

9.1 Register-Controlled Power Management

The RP bit in the CP0 *Status* register enables a standard software mechanism for placing the system into a low power state. The state of the RP bit is available externally via the *SL_RP* output signal. Three additional pins, *SL_EXL*, *SL_ERL*, and *EJ_DebugM* support the power management function by allowing the user to change the power state if an exception or error occurs while the core is in a low power state.

Setting the RP bit of the CP0 *Status* register causes the core to assert the *SL_RP* signal. The external agent can then decide whether to reduce the clock frequency and place the core into power down mode.

If an interrupt is taken while the device is in power down mode, that interrupt may need to be serviced depending on the needs of the application. The interrupt causes an exception which in turn causes the EXL bit to be set. The setting of the EXL bit causes the assertion of the *SL_EXL* signal on the external bus, indicating to the external agent that an interrupt has occurred. At this time the external agent can choose to either speed up the clocks and service the interrupt or let it be serviced at the lower clock speed.

The setting of the ERL bit causes the assertion of the *SL_ERL* signal on the external bus, indicating to the external agent that an error has occurred. At this time the external agent can choose to either speed up the clocks and service the error or let it be serviced at the lower clock speed.

Similarly, the *EJ_DebugM* signal indicates that the processor is in debug mode. Debug mode is entered when the processor takes a debug exception. If fast handling of this is desired, the external agent can speed up the clocks.

The core provides four power down signals that are part of the system interface. Three of the pins change state as the corresponding bits in the CP0 *Status* register are set or cleared. The fourth pin indicates that the processor is in debug mode:

- The *SL_RP* signal represents the state of the RP bit (27) in the CP0 *Status* register.
- The *SL_EXL* signal represents the state of the EXL bit (1) in the CP0 *Status* register.
- The *SL_ERL* signal represents the state of the ERL bit (2) in the CP0 *Status* register.

- The *EJ_DebugM* signal indicates that the processor has entered debug mode.

9.2 Instruction-Controlled Power Management

A second mechanism for invoking power down mode is through execution of the WAIT instruction. The WAIT instruction brings the processor into a low power state where the internal clocks are suspended and the pipeline is frozen. However, the internal timer and some of the input pins (*SI_Int[5:0]*, *SI_NMI*, *SI_Reset*, and *EJ_DINT*) continue to run. The clocks are not shut down until all bus and coprocessor transactions have completed. Once the CPU is in instruction controlled power management mode, any enabled interrupt, NMI, debug interrupt, or reset condition causes the CPU to exit this mode and resume normal operation. While the CPU is in this low-power mode, the *SI_SLEEP* signal is asserted to indicate to external agents what the state of the chip is.

9.2.1 Wait IE Ignore

A feature is included in the core that simplifies the task of using the WAIT instruction in the idle loop of an OS. The WAIT instruction is typically in block of code where the OS first checks to see if there is any pending work and if there is not, it will execute the WAIT as shown below.

```
if (!pending)
{
    wait();
}
```

There is a tricky race condition present in this code. If an interrupt arrives between the pending check and the WAIT instruction, the service routine will return and execute the WAIT and go to sleep. However, the interrupt may have been enabling some pending work to be done in the ‘bottom-half’ processing. If the core goes back to sleep, this pending work will not be done until the next interrupt arrives.

The OS can check to see if the interrupt was signalled in this window and adjust the EPC value to before the pending check, but this involves a fair amount of work. The Wait IE Ignore feature enables a simpler solution for the race condition. With this feature, a WAIT condition will be terminated by an active interrupt signal, even if that signal is prevented from causing an interrupt by Status_{IE} being clear or TCStatus_{IXMT} being set. This allows interrupts to be disabled in this section of code while still allowing the WAIT to complete.

An example of the assembly code for making use of this feature follows:

```
LEAF(r4k_wait)
.set push
.set noreorder
di t4                                # Clear Status.IE and preserve old value in t4
LONG_L t0, ti_flags($28)             # Get flag bits
andi t0, _TIF_NEED_RESCHED           # Isolate reschedule flag
bnez t0, 1f                          # branch around wait if pending work
nop
wait
1: mtc0t4, C0_Status                  # restore status register
.set pop
jr ra
nop
END(r4k_wait)
```

Note that this sequence would not be safe to execute on a core without this feature. In that case, a normal interrupt will generally not wake up the core if $Status_I\bar{E}=0$. The $Config7_{WII}$ bit indicates whether this feature is present on the core.

Instruction Set Overview

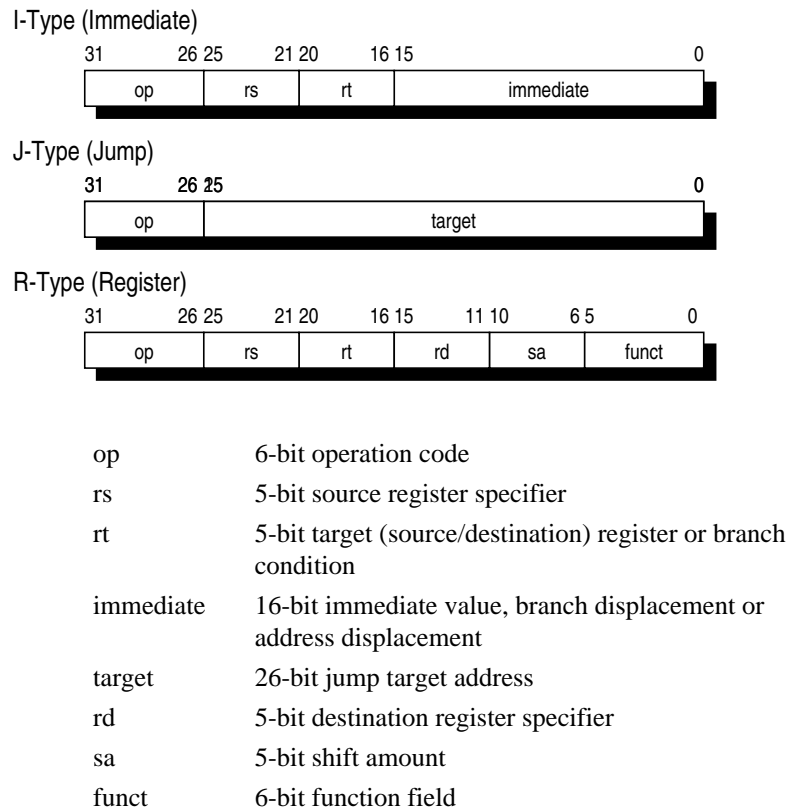
This chapter provides a general overview on the three CPU instruction set formats of the MIPS architecture: Immediate, Jump, and Register. Refer to [Chapter 12, “24K® Processor Core Instructions” on page 303](#) for a complete listing and description of instructions.

This chapter discusses the following topics

- [Section 10.1 “CPU Instruction Formats”](#)
- [Section 10.2 “Load and Store Instructions”](#)
- [Section 10.3 “Computational Instructions”](#)
- [Section 10.4 “Jump and Branch Instructions”](#)
- [Section 10.5 “Control Instructions”](#)
- [Section 10.6 “Coprocessor Instructions”](#)

10.1 CPU Instruction Formats

Each CPU instruction consists of a single 32-bit word, aligned on a word boundary. There are three instruction formats immediate (I-type), jump (J-type), and register (R-type)—as shown in [Figure 10.1](#). The use of a small number of instruction formats simplifies instruction decoding, allowing the compiler to synthesize more complicated (and less frequently used) operations and addressing modes from these three formats as needed.

Figure 10.1 Instruction Formats

10.2 Load and Store Instructions

Load and store instructions are immediate (I-type) instructions that move data between memory and the general registers. The only addressing mode that integer load and store instructions directly support is *base register plus 16-bit signed immediate offset*. Floating point load and store instructions can use either that addressing mode or *register plus register* indexed addressing.

10.2.1 Scheduling a Load Delay Slot

A load instruction that does not allow its result to be used by the instruction immediately following is called a *delayed load instruction*. The instruction slot immediately following this delayed load instruction is referred to as the *load delay slot*.

In a 24K core, the instruction immediately following a load instruction can use the contents of the loaded register; however in such cases hardware interlocks insert additional real cycles. Although not required, the scheduling of load delay slots can be desirable, both for performance and R-Series processor compatibility.

10.2.2 Defining Access Types

Access type indicates the size of a core data item to be loaded or stored, set by the load or store instruction opcode.

Regardless of access type or byte ordering (endianness), the address given specifies the low-order byte in the addressed field. For a big-endian configuration, the low-order byte is the most-significant byte; for a little-endian configuration, the low-order byte is the least-significant byte.

The access type, together with the three low-order bits of the address, define the bytes accessed within the addressed word as shown in Table 10.1. Only the combinations shown in Table 10.1 are permissible; other combinations cause address error exceptions.

Instruction fetches are either halfword accesses (MIPS16e™ code) or word accesses (32b code). These references will be impacted by endianness the same as load/store references of those sizes.

Table 10.1 Byte Access Within a Doubleword

| Access Type | Low-Order Address Bits | | | Bytes Accessed | | | | | | | | | | | | | | | |
|-------------|------------------------|---|---|---------------------------------|---|---|---|---|---|---|---|------------------------------------|---|---|---|---|---|---|---|
| | | | | Big Endian (63-----31-----0) | | | | | | | | Little Endian (63-----31-----0) | | | | | | | |
| | 2 | 1 | 0 | Byte | | | | | | | | Byte | | | | | | | |
| Doubleword | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| Word | 0 | 0 | 0 | 0 | 1 | 2 | 3 | | | | | | | | | 3 | 2 | 1 | 0 |
| | 1 | 0 | 0 | | | | | 4 | 5 | 6 | 7 | 7 | 6 | 5 | 4 | | | | |
| Triplebyte | 0 | 0 | 0 | 0 | 1 | 2 | | | | | | | | | | | 2 | 1 | 0 |
| | 0 | 0 | 1 | | 1 | 2 | 3 | | | | | | | | | 3 | 2 | 1 | |
| | 1 | 0 | 0 | | | | | 4 | 5 | 6 | | | 6 | 5 | 4 | | | | |
| | 1 | 0 | 1 | | | | | | 5 | 6 | 7 | 7 | 6 | 5 | | | | | |
| Halfword | 0 | 0 | 0 | 0 | 1 | | | | | | | | | | | | | 1 | 0 |
| | 0 | 1 | 0 | | | 2 | 3 | | | | | | | | | 3 | 2 | | |
| | 1 | 0 | 0 | | | | | 4 | 5 | | | | | 5 | 4 | | | | |
| | 1 | 1 | 0 | | | | | | | 6 | 7 | 7 | 6 | | | | | | |
| Byte | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | 0 |
| | 0 | 0 | 1 | | 1 | | | | | | | | | | | | | 1 | |
| | 0 | 1 | 0 | | | 2 | | | | | | | | | | | 2 | | |
| | 0 | 1 | 1 | | | | 3 | | | | | | | | | 3 | | | |
| | 1 | 0 | 0 | | | | | 4 | | | | | | | 4 | | | | |
| | 1 | 0 | 1 | | | | | | 5 | | | | | 5 | | | | | |
| | 1 | 1 | 0 | | | | | | | 6 | | | 6 | | | | | | |
| | 1 | 1 | 1 | | | | | | | | 7 | 7 | | | | | | | |

10.3 Computational Instructions

Computational instructions can be either in register (R-type) format, in which both operands are registers, or in immediate (I-type) format, in which one operand is a 16-bit immediate.

Computational instructions perform the following operations on register values:

- Arithmetic

Instruction Set Overview

- Logical
- Shift
- Count Leading Zeros/Ones
- Multiply
- Divide

These operations fit in the following four categories of computational instructions:

- ALU Immediate instructions
- Three-operand Register-type Instructions
- Shift Instructions
- Multiply And Divide Instructions

10.3.1 Cycle Timing for Multiply and Divide Instructions

Any multiply instruction in the integer pipeline is transferred to the multiplier as remaining instructions continue through the pipeline; the product of the multiply instruction is saved in the HI and LO registers. If the multiply instruction is followed by an MFHI or MFLO before the product is available, the pipeline interlocks until this product does become available. Refer to [Chapter 2, “Pipeline of the 24K® Core” on page 31](#) for more information on instruction latency and repeat rates.

10.4 Jump and Branch Instructions

Jump and branch instructions change the control flow of a program. All jump and branch instructions occur with a delay of one instruction: that is, the instruction immediately following the jump or branch (this is known as the instruction in the *delay slot*) always executes while the target instruction is being fetched from storage.

10.4.1 Overview of Jump Instructions

Subroutine calls in high-level languages are usually implemented with Jump or Jump and Link instructions, both of which are J-type instructions. In J-type format, the 26-bit target address shifts left 2 bits and combines with the high-order 4 bits of the current program counter to form an absolute address.

Returns, dispatches, and large cross-page jumps are usually implemented with the Jump Register or Jump and Link Register instructions. Both are R-type instructions that take the 32-bit byte address contained in one of the general purpose registers.

For more information about jump instructions, refer to the individual instructions in *MIPS32® Architecture Reference Manual, Volume II: The MIPS32® Instruction Set*.

10.4.2 Overview of Branch Instructions

All branch instruction target addresses are computed by adding the address of the instruction in the delay slot to the 16-bit *offset* (shifted left 2 bits and sign-extended to 32 bits). All branches occur with a delay of one instruction.

If a conditional branch likely is not taken, the instruction in the delay slot is nullified.

Branches, jumps, ERET, and DERET instructions should not be placed in the delay slot of a branch or jump.

10.5 Control Instructions

Control instructions allow the software to initiate traps; they are always R-type.

10.6 Coprocessor Instructions

CP0 instructions perform operations on the System Control Coprocessor registers to manipulate the memory management and exception handling facilities of the processor. Refer to [Chapter 12, “24K® Processor Core Instructions”](#) on [page 303](#) for a listing of CP0 instructions.

EJTAG Debug Support in the 24K® Core

The EJTAG debug logic in the 24K processor core is compliant with EJTAG Specification 3.20 and includes:

1. Standard core debug features
2. Optional hardware breakpoints
3. Standard Test Access Port (TAP) for a dedicated connection to a debug host
4. Optional MIPS Trace capability for program counter/data address/data value trace to On-chip memory or to Trace probe

This chapter contains the following sections:

- [Section 11.1 “Debug Control Register”](#)
- [Section 11.2 “Hardware Breakpoints”](#)
- [Section 11.3 “Test Access Port \(TAP\)”](#)
- [Section 11.4 “EJTAG TAP Registers”](#)
- [Section 11.5 “TAP Processor Accesses”](#)
- [Section 11.6 “PC Sampling”](#)
- [Section 11.7 “MIPS® Trace”](#)
- [Section 11.8 “PDtrace™ Registers \(Software Control\)”](#)
- [Section 11.9 “Trace Control Block \(TCB\) Registers \(Hardware Control\)”](#)
- [Section 11.10 “Enabling MIPS Trace”](#)
- [Section 11.11 “TCB Trigger Logic”](#)
- [Section 11.12 “MIPS Trace Cycle-by-Cycle Behavior”](#)
- [Section 11.13 “TCB On-Chip Trace Memory”](#)

11.1 Debug Control Register

The Debug Control Register (*DCR*) register controls and provides information about debug issues, and is always provided with the 24K core. The register is memory-mapped in drseg at offset 0x0.

The DataBrk and InstBrk bits indicate if hardware breakpoints are included in the implementation, and debug software is expected to read hardware breakpoint registers for additional information.

Hardware and software interrupts are maskable for non-debug mode with the INTE bit, which works in addition to the other mechanisms for interrupt masking and enabling. NMI is maskable in non-debug mode with the NMIE bit, and a pending NMI is indicated through the NMIP bit.

The SRE bit allows implementation dependent masking of some sources for reset. The 24K core does not distinguish between soft and hard reset, but typically only soft reset sources in the system would be maskable and hard sources such as the reset switch would not be. The soft reset masking should only be applied to a soft reset source if that source can be efficiently masked in the system, thus resulting in no reset at all. If that is not possible, then that soft reset source should not be masked, since a partial soft reset may cause the system to fail or hang. There is no automatic indication of whether the SRE is effective, so the user must consult system documentation.

The PE bit reflects the ProbEn bit from the EJTAG Control register (*ECR*), whereby the probe can indicate to the debug software that the probe will service dmseg accesses. The reset value in the table below takes effect on any CPU reset.

Figure 11.1 Debug Control Register

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-----|-----|-----|----|--|--|----|----|-----|-----|-----|----|-----|-----|-----|------|------|------|------|-----|----|---|---|--|---|--|---|--|---|--|---|---|
| 31 | 30 | 29 | 28 | | | | | 18 | 17 | 16 | 15 | | 14 | 13 | | 11 | 10 | | 9 | 8 | 6 | 5 | | 4 | | 3 | | 2 | | 1 | 0 |
| Res | ENM | Res | | | | DB | IB | IVM | DVM | Res | | CBT | PCS | PCR | PCSe | INTE | NMIE | NMIP | SRE | PE | | | | | | | | | | | |

Table 11.1 Debug Control Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| Res | 31:30 | Reserved | R | 0 |
| ENM | 29 | Endianess in Kernel and Debug mode 0: Little Endian 1: Big Endian | R | Preset |
| Res | 28:18 | Reserved | R | 0 |
| DB | 17 | Data Break Implemented 0: No Data Break feature implemented 1: Data Break feature is implemented | R | Preset |
| IB | 16 | Instruction Break Implemented 0: No Instruction Break feature implemented 1: Instruction Break feature is implemented | R | Preset |
| IVM | 15 | Inverted Value Match 0: Feature is not supported 1: Feature is supported | R | 0 |
| DVM | 14 | Data Value Match Storage 0: Feature is not supported 1: Feature is supported | R | 0 |
| Res | 13:11 | Reserved | R | 0 |

Table 11.1 Debug Control Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|--|
| Name | Bit(s) | | | |
| CBT | 10 | Complex Break and Trigger 0: Feature is not implemented 1: Feature is implemented | R | 0 |
| PCS | 9 | Program Counter Sampling Implemented 0: No PC Sampling implemented 1: PC Sampling implemented | R | 1 |
| PCR | 8:6 | PC Sampling Rate: Values from 0 to 7 map to 2^5 to 2^{12} respectively. That is, a PC sample is written out every 32, 64, 128, 256, 512, 1024, 2048, or 4096 cycles. The external probe or software is allowed to set this value to the desired sample rate | R/W | 7 |
| PCSe | 5 | PC Sampling Enable. Set to 1 to enable PC sampling | R | 0 |
| INTE | 4 | Interrupt Enable in Normal Mode. This bit provides the hardware and software interrupt enable for non-debug mode, in addition to other masking mechanisms: 0: Interrupts disabled. 1: Interrupts enabled (depending on other enabling mechanisms). | R/W | 1 |
| NMIE | 3 | Non-Maskable Interrupt Enable for non-debug mode 0: NMI disabled. 1: NMI enabled. | R/W | 1 |
| NMIP | 2 | NMI Pending Indication. 0: No NMI pending. 1: NMI pending. | R | 0 |
| SRE | 1 | Soft Reset Enable This bit allows the system to mask soft resets. The core does not internally mask resets. Rather the state of this bit appears on the EJ_SRstE external output signal, allowing the system to mask soft resets if desired. | R/W | 1 |
| PE | 0 | Probe Enable This bit reflects the ProbEn bit in the EJTAG Control register. 0: No accesses to dmseg allowed 1: EJTAG probe services accesses to dmseg | R | Same value as ProbEn in ECR (see Table 11.25) |

11.2 Hardware Breakpoints

Hardware breakpoints provide for the comparison by hardware of executed instructions and data load/store transactions. It is possible to set instruction breakpoints on addresses even in ROM area,. Data breakpoints can be set to cause a debug exception on a specific data transaction. Instruction and data hardware breakpoints are alike for many aspects, and are thus described in parallel in the following. The term hardware is not applied to breakpoint, unless required to distinguish it from software breakpoint.

There are two types of simple hardware breakpoints implemented in the 24K core; Instruction breakpoints and Data breakpoints.

A core may be configured with the following breakpoint options:

- Zero or four instruction breakpoints
- Zero or two data breakpoints

11.2.1 Features of Instruction Breakpoint

Instruction breaks occur on instruction fetch operations and the break is set on the virtual address used by the instruction fetch unit. Instruction breaks can also be made on the ASID value used by the TLB-based MMU. Finally, a mask can be applied to the virtual address to set breakpoints on a range of instructions.

Instruction breakpoints compare the virtual address of the executed instructions (PC) and the ASID with the registers for each instruction breakpoint including masking of address and ASID. When an instruction breakpoint matches, a debug exception and/or a trigger is generated. An internal bit in the instruction breakpoint registers is set to indicate that the match occurred.

11.2.2 Features of Data Breakpoint

Data breakpoints occur on load/store transactions. Breakpoints are set on virtual address and ASID values, similar to the Instruction breakpoint. Data breakpoints can be set on a load, a store or both. Data breakpoints can also be set based on the value of the load/store operation. Finally, masks can be applied to both the virtual address and the load/store value.

Data breakpoints compare the transaction type (TYPE), which may be load or store, the virtual address of the transaction (ADDR), the ASID, accessed bytes (BYTELANE) and data value (DATA), with the registers for each data breakpoint including masking or qualification on the transaction properties. When a data breakpoint matches, a debug exception and/or a trigger is generated, and an internal bit in the data breakpoint registers is set to indicate that the match occurred. The match is precise in that the debug exception or trigger occurs on the instruction that caused the breakpoint to match.

11.2.3 Instruction Breakpoint Registers Overview

The register with implementation indication and status for instruction breakpoints in general is shown in [Table 11.2](#).

Table 11.2 Overview of Status Register for Instruction Breakpoints

| Register Mnemonic | Register Name and Description |
|-------------------|-------------------------------|
| <i>IBS</i> | Instruction Breakpoint Status |

The four instruction breakpoints are numbered 0 to 3 for registers and breakpoints, and the number is indicated by n. The registers for each breakpoint are shown in [Table 11.3](#).

Table 11.3 Overview of Registers for Each Instruction Breakpoint

| Register Mnemonic | Register Name and Description |
|-------------------|---------------------------------------|
| <i>IBAn</i> | Instruction Breakpoint Address n |
| <i>IBMn</i> | Instruction Breakpoint Address Mask n |
| <i>IBASIDn</i> | Instruction Breakpoint ASID n |
| <i>IBCn</i> | Instruction Breakpoint Control n |

11.2.4 Data Breakpoint Registers Overview

The register with implementation indication and status for data breakpoints in general is shown in [Table 11.4](#).

Table 11.4 Overview of Status Register for Data Breakpoints

| Register Mnemonic | Register Name and Description |
|-------------------|-------------------------------|
| <i>DBS</i> | Data Breakpoint Status |

The two data breakpoints are numbered 0 and 1 for registers and breakpoints, and the number is indicated by *n*. The registers for each breakpoint are shown in [Table 11.5](#).

Table 11.5 Overview of Registers for Each Data Breakpoint

| Register Mnemonic | Register Name and Description |
|-------------------|---------------------------------------|
| <i>DBAn</i> | Data Breakpoint Address <i>n</i> |
| <i>DBMn</i> | Data Breakpoint Address Mask <i>n</i> |
| <i>DBASIDn</i> | Data Breakpoint ASID <i>n</i> |
| <i>DBCn</i> | Data Breakpoint Control <i>n</i> |
| <i>DBVn</i> | Data Breakpoint Value <i>n</i> |

11.2.5 Conditions for Matching Breakpoints

A number of conditions must be fulfilled in order for a breakpoint to match on an executed instruction or a data transaction, and the conditions for matching instruction and data breakpoints are described below. The breakpoints only match for instructions executed in non-debug mode, thus never on instructions executed in debug mode.

The match of an enabled breakpoint can either generate a debug exception or a trigger indication. The *BE* and/or *TE* bits in the *IBCn* or *DBCn* registers are used to enable the breakpoints.

Debug software should not configure breakpoints to compare on an ASID value unless a TLB is present in the implementation.

11.2.5.1 Conditions for Matching Instruction Breakpoints

When an instruction breakpoint is enabled, that breakpoint is evaluated for the address of every executed instruction in non-debug mode, including execution of instructions at an address causing an address error on an instruction fetch. The breakpoint is not evaluated on instructions from a speculative fetch or execution, nor for addresses which are unaligned with an executed instruction.

A breakpoint match depends on the virtual address of the executed instruction (PC) which can be masked at bit level, and match also can include an optional compare of ASID. The registers for each instruction breakpoint have the values and mask used in the compare, and the equation that determines the match is shown below in C-like notation.

```
IB_match =
    ( ! IBCn_ASIDuse || ( ASID == IBASIDn_ASID ) ) &&
    ( <all 1's> == ( IBMn_IBM | ~ ( PC ^ IBAn_IBA ) ) &&
      ( ( IBMn_ISAM | ~(ISAMode ^ IBAn_ISA) ) ) )
```

The match indication for instruction breakpoints is always precise, i.e. indicated on the instruction causing the *IB_match* to be true.

11.2.5.2 Conditions for Matching Data Breakpoints

When a data breakpoint is enabled, that breakpoint is evaluated for every data transaction due to a load/store instruction executed in non-debug mode, including load/store for coprocessor and transactions causing an address error on data access. The breakpoint is not evaluated due to a PREF instruction or other transactions which are not part of explicit load/store transactions in the execution flow, nor for addresses which are not the explicit load/store source or destination address.

A breakpoint match depends on the transaction type (TYPE) as load or store, the address, and optionally the data value of a transaction. The registers for each data breakpoint have the values and mask used in the compare, and the equation that determines the match is shown below in C-like notation.

The overall match equation is the DB_match.

```
DB_match =
    ( ( ( TYPE == load ) && ! DBCn_NoLB ) ||
      ( ( TYPE == store ) && ! DBCn_NoSB ) ) &&
    DB_addr_match && ( DB_no_value_compare || DB_value_match )
```

The match on the address part, DB_addr_match, depends on the virtual address of the transaction (ADDR), the ASID value, and the accessed bytes (BYTELANE) where BYTELANE[0] is 1 only if the byte at bits [7:0] on the bus is accessed, and BYTELANE[1] is 1 only if the byte at bits [15:8] is accessed, etc. The DB_addr_match is shown below.

```
DB_addr_match =
    ( ! DBCn_ASIDuse || ( ASID == DBASIDn_ASID ) ) &&
    ( <all 1's> == ( DBMn_DBM | ~ ( ADDR ^ DBAn_DBA ) ) ) &&
    ( <all 0's> != ( ~ BAI & BYTELANE ) )
```

The size of $DBCn_{BAI}$ and BYTELANE is 8 bits. They are 8 bits to allow for data value matching on doubleword floating point loads and stores. For non-doubleword loads and stores, only the lower 4 bits will be used.

Data value compare is included in the match condition for the data breakpoint depending on the bytes (BYTELANE as described above) accessed by the transaction, and the contents of breakpoint registers. The DB_no_value_compare is shown below.

```
DB_no_value_compare =
    ( <all 1's> == ( DBCn_BLM | DBCn_BAI | ~ BYTELANE ) )
```

The size of $DBCn_{BLM}$, $DBCn_{BAI}$ and BYTELANE is 8 bits.

In case a data value compare is required, DB_no_value_compare is false, then the data value from the data bus (DATA) is compared and masked with the registers for the data breakpoint. The endianness is not considered in these match equations for value, as the compare uses the data bus value directly, thus debug software is responsible for setup of the breakpoint corresponding with endianness.

```
DB_value_match =
    ( ( DATA[7:0] == DBVn_DBV[7:0] ) || !BYTELANE[0] || DBCn_BLM[0] || DBCn_BAI[0] ) &&
    ( ( DATA[15:8] == DBVn_DBV[15:8] ) || !BYTELANE[1] || DBCn_BLM[1] || DBCn_BAI[1] ) &&
    ( ( DATA[23:16] == DBVn_DBV[23:16] ) || !BYTELANE[2] || DBCn_BLM[2] || DBCn_BAI[2] ) &&
    ( ( DATA[31:24] == DBVn_DBV[31:24] ) || !BYTELANE[3] || DBCn_BLM[3] || DBCn_BAI[3] ) &&
    ( ( DATA[39:32] == DBVn_DBV[39:32] ) || !BYTELANE[4] || DBCn_BLM[4] || DBCn_BAI[4] ) &&
    ( ( DATA[47:40] == DBVn_DBV[47:40] ) || !BYTELANE[5] || DBCn_BLM[5] || DBCn_BAI[5] ) &&
    ( ( DATA[55:48] == DBVn_DBV[55:48] ) || !BYTELANE[6] || DBCn_BLM[6] || DBCn_BAI[6] ) &&
    ( ( DATA[63:56] == DBVn_DBV[63:56] ) || !BYTELANE[7] || DBCn_BLM[7] || DBCn_BAI[7] ) )
```

The match for a data breakpoint without value compare is always precise, since the match expression is fully evaluated at the time the load/store instruction is executed. A true DB_match can thereby be indicated on the very same instruction causing the DB_match to be true. The match for data breakpoints with value compare is always imprecise.

11.2.6 Debug Exceptions from Breakpoints

Instruction and data breakpoints may be set up to generate a debug exception when the match condition is true, as described below.

11.2.6.1 Debug Exception by Instruction Breakpoint

If the breakpoint is enabled by BE bit in the *IBCn* register, then a debug instruction break exception occurs if the IB_match equation is true. The corresponding BS[n] bit in the *IBS* register is set when the breakpoint generates the debug exception.

The debug instruction break exception is always precise, so the *DEPC* register and DBD bit in the *Debug* register point to the instruction that caused the IB_match equation to be true.

The instruction receiving the debug exception does not update any registers due to the instruction, nor does any load or store by that instruction occur. Thus a debug exception from a data breakpoint can not occur for instructions receiving a debug instruction break exception.

The debug handler usually returns to the instruction causing the debug instruction break exception, whereby the instruction is executed. Debug software is responsible for disabling the breakpoint when returning to the instruction, otherwise the debug instruction break exception reoccurs.

11.2.6.2 Debug Exception by Data Breakpoint

If the breakpoint is enabled by BE bit in the *DBCn* register, then a debug exception occurs when the DB_match condition is true. The corresponding BS[n] bit in the *DBS* register is set when the breakpoint generates the debug exception. A matching data breakpoint generates either a precise or imprecise debug exception

Debug Data Break Load/Store Exception as a Precise Debug Exception

A precise debug data break exception occurs when a data breakpoint without value compare indicates a match. In this case the *DEPC* register and DBD bit in the *Debug* register points to the instruction that caused the DB_match equation to be true.

The instruction causing the debug data break exception does not update any registers due to the instruction, and the following applies to the load or store transaction causing the debug exception:

- A store transaction is not allowed to complete the store to the memory system.
- A load transaction with no data value compare, i.e. where the DB_no_value_compare is true for the match, is not allowed to complete the load.

The result of this is that the load or store instruction causing the debug data break exception appears as not executed.

If both data breakpoints without and with data value compare would match the same transaction and generate a debug exception, then the rules shown in Table 11.6 apply with respect to updating the BS[n] bits.

Table 11.6 Rules for Update of BS Bits on Data Breakpoint Exceptions

| Instruction | Breakpoints that Match | | Update of BS Bits for Matching Data Breakpoints | |
|-------------|------------------------|--------------------|---|---|
| | Without Value Compare | With Value Compare | Without Value Compare | With Value Compare |
| Load/Store | One or more | None | BS bits set for all | (No matching break-points) |
| Load | One or more | One or more | BS bits set for all | Unchanged BS bits since load of data value does not occur so match of the breakpoint cannot be determined |
| Load | None | One or more | (No matching break-points) | BS bits set for all |
| Store | One or more | One or more | BS bits set for all | BS bits set for all |
| Store | None | One or more | (No matching break-points) | BS bits set for all |

Any BS[n] bit set prior to the match and debug exception are kept set, since BS[n] bits are only cleared by debug software.

The debug handler usually returns to the instruction causing the debug data break exception, whereby the instruction is re-executed. Debug software is responsible for disabling breakpoints when returning to the instruction, otherwise the debug data break exception will reoccur.

Debug Data Break Load/Store Exception as a Imprecise Debug Exception

An Debug Data Break Load/Store Imprecise exception occurs when a data breakpoint indicates an imprecise match. Imprecise matches are generated when data value compare is used. In this case, the DEPC register and DBD bit in the Debug register point to an instruction later in the execution flow rather than at the load/store instruction that caused the DB_match equation to be true.

The load/store instruction causing the Debug Data Break Load/Store Imprecise exception always updates the destination register and completes the access to the external memory system. Therefore this load/store instruction is not re-executed on return from the debug handler, because the DEPC register and DBD bit do not point to that instruction.

Several imprecise data breakpoints can be pending at a given time, if the bus system supports multiple outstanding data accesses. The breakpoints are evaluated as the accesses finalize, and a Debug Data Break Load/Store Imprecise exception is generated only for the first one matching. Both the first and succeeding matches cause corresponding BS bits and DDBLImpr/DDBSImpr to be set, but no debug exception is generated for succeeding matches because the processor is already in Debug Mode. Similarly, if a debug exception had already occurred at the time of the first match (for example, due to a precise debug exception), then all matches cause the corresponding BS bits and DDBLImpr/DDBSImpr to be set, but no debug exception is generated because the processor is already in Debug Mode.

The SYNC instruction, followed by appropriate spacing must be executed before the BS bits and DDBLImpr/DDBSImpr bits are accessed for read or write. This delay ensures that these bits are fully updated.

Any BS bit set prior to the match and debug exception are kept set, because only debug software can clear the BS bits.

11.2.7 Breakpoint used as TriggerPoint

Both instruction and data hardware breakpoints can be setup by software so a matching breakpoint does not generate a debug exception, but only an indication through the BS[n] bit. The TE bit in the *IBCn* or *DBCn* register controls if an instruction or data breakpoint is used as a so-called triggerpoint. The triggerpoints are, like breakpoints, only compared for instructions executed in non-debug mode.

The BS[n] bit in the *IBS* or *DBS* register is set when the respective IB_match or DB_match bit is true.

The triggerpoint feature can be used to start and stop tracing. See [Section 11.10 “Enabling MIPS Trace”](#) for details.

11.2.8 Instruction Breakpoint Registers

The registers for instruction breakpoints are described below. These registers have implementation information and are used to set up the instruction breakpoints. All registers are in drseg, and the addresses are shown in [Table 11.7](#).

Table 11.7 Addresses for Instruction Breakpoint Registers

| Offset in drseg | Register Mnemonic | Register Name and Description |
|--|-------------------|---------------------------------------|
| 0x1000 | <i>IBS</i> | Instruction Breakpoint Status |
| 0x1100 + n * 0x100 | <i>IBAn</i> | Instruction Breakpoint Address n |
| 0x1108 + n * 0x100 | <i>IBMn</i> | Instruction Breakpoint Address Mask n |
| 0x1110 + n * 0x100 | <i>IBASIDn</i> | Instruction Breakpoint ASID n |
| 0x1118 + n * 0x100 | <i>IBCn</i> | Instruction Breakpoint Control n |
| n is breakpoint number in range 0 to 3 | | |

An example of some of the registers; *IBA0* is at offset 0x1100 and *IBC2* is at offset 0x1318.

11.2.8.1 Instruction Breakpoint Status (IBS) Register

Compliance Level: Implemented only if instruction breakpoints are implemented.

The Instruction Breakpoint Status (*IBS*) register holds implementation and status information about the instruction breakpoints.

The ASID applies to all the instruction breakpoints.

Figure 11.2 IBS Register Format

| | | | | | | | | | | | | | |
|-----|---------|-----|-----|-----|----|----|--|--|--|--|---|----|---|
| 31 | 30 | 29 | 28 | 27 | 24 | 23 | | | | | 4 | 3 | 0 |
| Res | ASIDsup | Res | BCN | Res | | | | | | | | BS | |

Table 11.8 IBS Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|--------|--|--------------|--------------------------|
| Name | Bit(s) | | | |
| Res | 31 | Must be written as zero; returns zero on read. | R | 0 |
| ASIDsup | 30 | Indicates that ASID compare is supported in instruction breakpoints. 0: No ASID compare. 1: ASID compare (IBASIDn register implemented). 1: Supported 0: Not supported | R | Fixed MMU - 0 TLB - 1 |
| Res | 29:28 | Must be written as zero; returns zero on read. | R | 0 |
| BCN | 27:24 | Number of instruction breakpoints implemented. | R | 4 |
| Res | 23:4 | Must be written as zero; returns zero on read. | R | 0 |
| BS | 3:0 | Break status for breakpoint n is at BS[n], with n from 0 to 3. The bit is set to 1 when the condition for the corresponding breakpoint has matched. | R/W | Undefined |

11.2.8.2 Instruction Breakpoint Address n (IBAn) Register

Compliance Level: Implemented only for implemented instruction breakpoints.

The Instruction Breakpoint Address *n* (*IBAn*) register has the address used in the condition for instruction breakpoint *n*.

Figure 11.3 IBAn Register Format

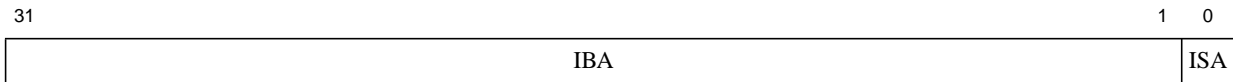


Table 11.9 IBAn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| IBA | 31:1 | Instruction breakpoint address for condition. | R/W | Undefined |
| ISA | 0 | Instruction breakpoint ISA mode for condition | R/W | Undefined |

11.2.8.3 Instruction Breakpoint Address Mask n (IBMn) Register

Compliance Level: Implemented only for implemented instruction breakpoints.

The Instruction Breakpoint Address Mask *n* (*IBMn*) register has the mask for the address compare used in the condition for instruction breakpoint *n*.

Figure 11.4 IBMn Register Format

| | | |
|-----|---|------|
| 31 | 1 | 0 |
| IBM | | ISAM |

Table 11.10 IBMn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| IBM | 31:1 | Instruction breakpoint address mask for condition: 0: Corresponding address bit not masked. 1: Corresponding address bit masked. | R/W | Undefined |
| ISAM | 0 | Instruction breakpoint ISA mode mask for condition: 0: ISA mode considered for match condition 1: ISA mode masked | R/W | Undefined |

11.2.8.4 Instruction Breakpoint ASID n (IBASIDn) Register

Compliance Level: Implemented only for implemented instruction breakpoints.

For processors with a TLB based MMU, this register is used to define an ASID value to be used in the match expression. For cores with a FM MMU, this register is reserved and reads as 0.

Figure 11.5 IBASIDn Register Format

| | | | |
|-----|---|---|------|
| 31 | 8 | 7 | 0 |
| Res | | | ASID |

Table 11.11 IBASIDn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| Res | 31:8 | Must be written as zero; returns zero on read. | R | 0 |
| ASID | 7:0 | Instruction breakpoint ASID value for a compare. | R/W | Undefined |

11.2.8.5 Instruction Breakpoint Control n (IBCN) Register

Compliance Level: Implemented only for implemented instruction breakpoints.

The Instruction Breakpoint Control *n* (IBCN) register controls the setup of instruction breakpoint *n*.

Figure 11.6 IBCn Register Format

| | | | | | | | | |
|-----|----|---------|-----|-----|---|----|-----|----|
| 31 | 24 | 23 | 22 | 21 | 3 | 2 | 1 | 0 |
| Res | | ASIDuse | Res | Res | | TE | Res | BE |

Table 11.12 IBCn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|-------|---|--------------|-------------|
| Name | Bits | | | |
| Res | 31:24 | Must be written as zero; returns zero on read. | R | 0 |
| ASIDuse | 23 | Use ASID value in compare for instruction breakpoint n: 0: Don't use ASID value in compare 1: Use ASID value in compare | R/W | Undefined |
| Res | 22 | Must be written as zero; returns zero on read | R | 0 |
| Res | 21:3 | Must be written as zero; returns zero on read. | R | 0 |
| TE | 2 | Use instruction breakpoint n as triggerpoint: 0: Don't use it as triggerpoint 1: Use it as triggerpoint | R/W | 0 |
| Res | 1 | Must be written as zero; returns zero on read. | R | 0 |
| BE | 0 | Use instruction breakpoint n as breakpoint: 0: Don't use it as breakpoint 1: Use it as breakpoint | R/W | 0 |

11.2.9 Data Breakpoint Registers

The registers for data breakpoints are described below. These registers have implementation information and are used to setup the data breakpoints. All registers are in drseg, and the addresses are shown in [Table 11.13](#).

Table 11.13 Addresses for Data Breakpoint Registers

| Offset in drseg | Register Mnemonic | Register Name and Description |
|----------------------------------|-------------------|--------------------------------|
| 0x2000 | <i>DBS</i> | Data Breakpoint Status |
| 0x2100 + 0x100 * n | <i>DBAn</i> | Data Breakpoint Address n |
| 0x2108 + 0x100 * n | <i>DBMn</i> | Data Breakpoint Address Mask n |
| 0x2110 + 0x100 * n | <i>DBASIDn</i> | Data Breakpoint ASID n |
| 0x2118 + 0x100 * n | <i>DBCn</i> | Data Breakpoint Control n |
| 0x2120 + 0x100 * n | <i>DBVn</i> | Data Breakpoint Value n |
| 0x2124 + 0x100*n | <i>DBVHn</i> | Data Breakpoint Value High n |
| n is breakpoint number as 0 or 1 | | |

An example of some of the registers; *DBM0* is at offset 0x2108 and *DBV1* is at offset 0x2220.

11.2.9.1 Data Breakpoint Status (DBS) Register

Compliance Level: Implemented if data breakpoints are implemented.

The Data Breakpoint Status (*DBS*) register holds implementation and status information about the data breakpoints.

The `ASIDsup` field indicates whether ASID compares are supported.

Figure 11.7 DBS Register Format

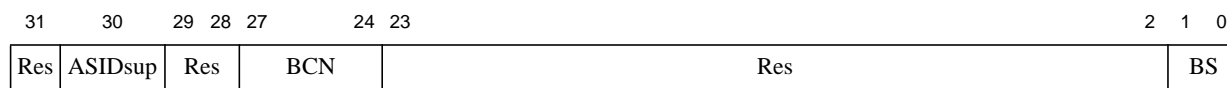


Table 11.14 DBS Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|---------------------------|
| Name | Bit(s) | | | |
| Res | 31 | Must be written as zero; returns zero on read. | R | 0 |
| ASID | 30 | Indicates that ASID compares are supported in data breakpoints. 0: Not supported 1: Supported | R | TLB MMU - 1 FM MMU - 0 |
| Res | 29:28 | Must be written as zero; returns zero on read. | R | 0 |
| BCN | 27:24 | Number of data breakpoints implemented. | R | 2 |
| Res | 23:2 | Must be written as zero; returns zero on read. | R | 0 |
| BS | 1:0 | Break status for breakpoint n is at BS[n], with n from 0 to 1. The bit is set to 1 when the condition for the corresponding breakpoint has matched. | R/W0 | Undefined |

11.2.9.2 Data Breakpoint Address n (DBAn) Register

Compliance Level: Implemented only for implemented data breakpoints.

The Data Breakpoint Address n (*DBAn*) register has the address used in the condition for data breakpoint n.

Figure 11.8 DBAn Register Format

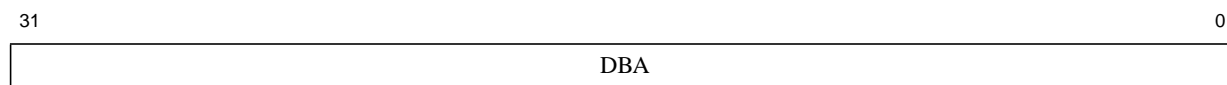


Table 11.15 DBAn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| DBA | 31:0 | Data breakpoint address for condition. | R/W | Undefined |

11.2.9.3 Data Breakpoint Address Mask n (DBMn) Register

Compliance Level: Implemented only for implemented data breakpoints.

The Data Breakpoint Address Mask n (*DBMn*) register has the mask for the address compare used in the condition for data breakpoint n.

Figure 11.9 DBMn Register Format



Table 11.16 DBMn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| DBM | 31:0 | Data breakpoint address mask for condition: 0: Corresponding address bit not masked 1: Corresponding address bit masked | R/W | Undefined |

11.2.9.4 Data Breakpoint ASID n (DBASIDn) Register

Compliance Level: Implemented only for implemented data breakpoints.

For processors with a TLB based MMU, this register is used to define an ASID value to be used in the match expression. For cores with the FM MMU, this register is reserved and reads as 0.

Figure 11.10 DBASIDn Register Format

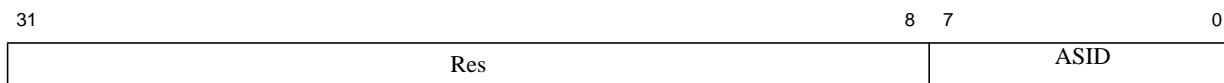


Table 11.17 DBASIDn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| Res | 31:8 | Must be written as zero; returns zero on read. | R | 0 |
| ASID | 7:0 | Data breakpoint ASID value for compares. | R/W | Undefined |

11.2.9.5 Data Breakpoint Control n (DBCn) Register

Compliance Level: Implemented only for implemented data breakpoints.

The Data Breakpoint Control *n* (DBCn) register controls the setup of data breakpoint *n*.

Figure 11.11 DBCn Register Format

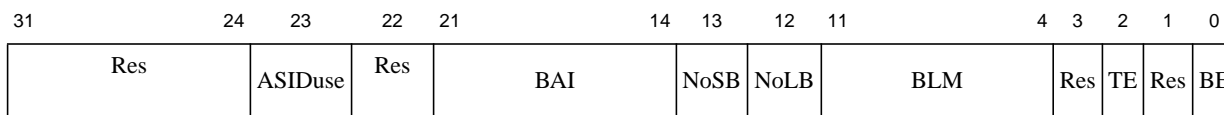


Table 11.18 DBCn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|---------|-------|--|--------------|-------------|
| Name | Bits | | | |
| Res | 31:24 | Must be written as zero; returns zero on reads. | R | 0 |
| ASIDuse | 23 | Use ASID value in compare for data breakpoint n: 0: Don't use ASID value in compare 1: Use ASID value in compare | R/W | Undefined |
| Res | 22 | Must be written as zero; returns zero on reads | R | 0 |
| BAI | 21:14 | Byte access ignore controls ignore of access to a specific byte. BAI[0] ignores access to byte at bits [7:0] of the data bus, BAI[1] ignores access to byte at bits [15:8], etc. 0: Condition depends on access to corresponding byte 1: Access for corresponding byte is ignored | R/W | Undefined |
| NoSB | 13 | Controls if condition for data breakpoint is not fulfilled on a store transaction: 0: Condition may be fulfilled on store transaction 1: Condition is never fulfilled on store transaction | R/W | Undefined |
| NoLB | 12 | Controls if condition for data breakpoint is not fulfilled on a load transaction: 0: Condition may be fulfilled on load transaction 1: Condition is never fulfilled on load transaction | R/W | Undefined |
| BLM | 11:4 | Byte lane mask for value compare on data breakpoint. BLM[0] masks byte at bits [7:0] of the data bus, BLM[1] masks byte at bits [15:8], etc.: 0: Compare corresponding byte lane 1: Mask corresponding byte lane | R/W | Undefined |
| Res | 3 | Must be written as zero; returns zero on reads. | R | 0 |
| TE | 2 | Use data breakpoint n as triggerpoint: 0: Don't use it as triggerpoint 1: Use it as triggerpoint | R/W | 0 |
| Res | 1 | Must be written as zero; returns zero on reads. | R | 0 |
| BE | 0 | Use data breakpoint n as breakpoint: 0: Don't use it as breakpoint 1: Use it as breakpoint | R/W | 0 |

11.2.9.6 Data Breakpoint Value n (DBVn) Register

Compliance Level: Implemented only for implemented data breakpoints.

The Data Breakpoint Value n (*DBVn*) register has the value used in the condition for data breakpoint n.

Figure 11.12 DBVn Register Format

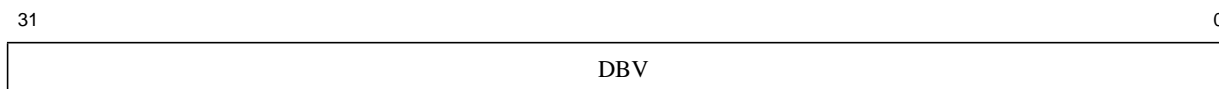


Table 11.19 DBVn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--------------------------------------|--------------|-------------|
| Name | Bit(s) | | | |
| DBV | 31:0 | Data breakpoint value for condition. | R/W | Undefined |

11.2.9.7 Data Breakpoint Value High n (DBVHn) Register

Compliance Level: Implemented only for implemented data breakpoints.

The Data Breakpoint Value High n (*DBVHn*) register has the value used in the condition for data breakpoint n.

Figure 11.13 DBVHn Register Format



Table 11.20 DBVHn Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| DBVH | 31:0 | Data breakpoint value high for condition. This register provides the high order bits [63:32] for data value on double-word floating point loads and stores. | R/W | Undefined |

11.3 Test Access Port (TAP)

The following main features are supported by the TAP module:

- 5-pin industry standard JTAG Test Access Port (*TCK*, *TMS*, *TDI*, *TDO*, *TRST_N*) interface which is compatible with IEEE Std. 1149.1.
- Target chip and EJTAG feature identification available through the Test Access Port (TAP) controller.
- The processor can access external memory on the EJTAG Probe serially through the EJTAG pins. This is achieved through Processor Access (PA), and is used to eliminate the use of the system memory for debug routines.
- Support for both ROM based debugger and debugging both through TAP.

11.3.1 EJTAG Internal and External Interfaces

The external interface of the EJTAG module consists of the 5 signals defined by the IEEE standard.

Table 11.21 EJTAG Interface Pins

| Pin | Type | Description |
|---------------|------|---|
| <i>TCK</i> | I | Test Clock Input Input clock used to shift data into or out of the Instruction or data registers. The <i>TCK</i> clock is independent of the processor clock, so the EJTAG probe can drive <i>TCK</i> independently of the processor clock frequency. The core signal for this is called <i>EJ_TCK</i> |
| <i>TMS</i> | I | Test Mode Select Input The <i>TMS</i> input signal is decoded by the TAP controller to control test operation. <i>TMS</i> is sampled on the rising edge of <i>TCK</i> . The core signal for this is called <i>EJ_TMS</i> |
| <i>TDI</i> | I | Test Data Input Serial input data (<i>TDI</i>) is shifted into the Instruction register or data registers on the rising edge of the <i>TCK</i> clock, depending on the TAP controller state. The core signal for this is called <i>EJ_TDI</i> |
| <i>TDO</i> | O | Test Data Output Serial output data is shifted from the Instruction or data register to the <i>TDO</i> pin on the falling edge of the <i>TCK</i> clock. When no data is shifted out, the <i>TDO</i> is 3-stated. The core signal for this is called <i>EJ_TDO</i> with output enable controlled by <i>EJ_TDOzstate</i> . |
| <i>TRST_N</i> | I | Test Reset Input (Optional pin) The <i>TRST_N</i> pin is an active-low signal for asynchronous reset of the TAP controller and instruction in the TAP module, independent of the processor logic. The processor is not reset by the assertion of <i>TRST_N</i> . The core signal for this is called <i>EJ_TRST_N</i> This signal is optional, but power-on reset must apply a low pulse on this signal at power-on and then leave it high, in case the signal is not available as a pin on the chip. If available on the chip, then it must be low on the board when the EJTAG debug features are unused by the probe. |

11.3.2 Test Access Port Operation

The TAP controller is controlled by the Test Clock (*TCK*) and Test Mode Select (*TMS*) inputs. These two inputs determine whether an the Instruction register scan or data register scan is performed. The TAP consists of a small controller, driven by the *TCK* input, which responds to the *TMS* input as shown in the state diagram in [Figure 11.14](#). The TAP uses both clock edges of *TCK*. *TMS* and *TDI* are sampled on the rising edge of *TCK*, while *TDO* changes on the falling edge of *TCK*.

At power-up the TAP is forced into the *Test-Logic-Reset* by low value on *TRST_N*. The TAP instruction register is thereby reset to IDCODE. No other parts of the EJTAG hardware are reset through the *Test-Logic-Reset* state.

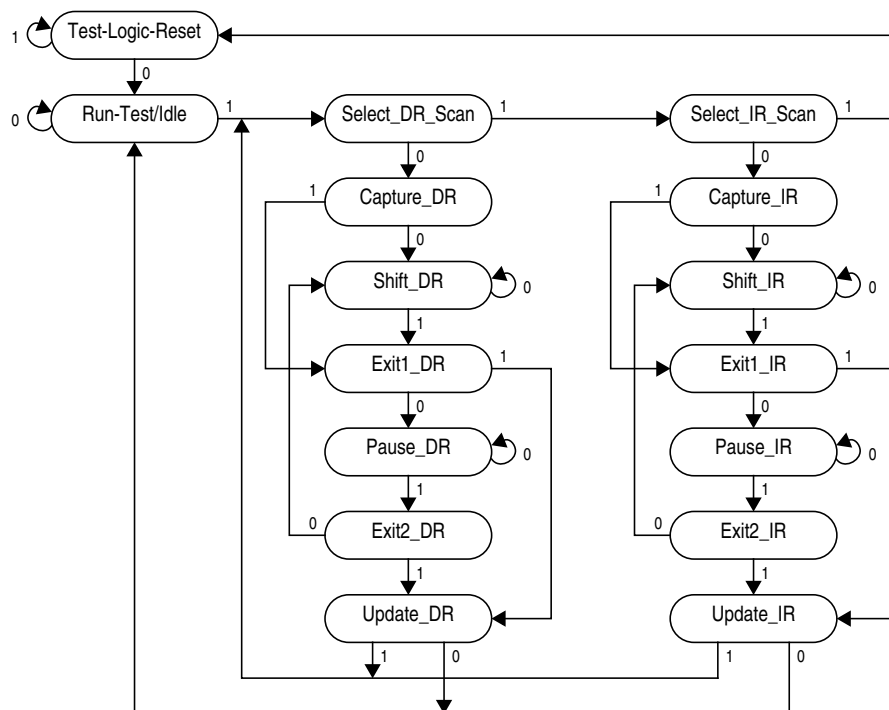
When test access is required, a protocol is applied via the *TMS* and *TCK* inputs, causing the TAP to exit the *Test-Logic-Reset* state and move through the appropriate states. From the *Run-Test/Idle* state, an Instruction register scan or a data register scan can be issued to transition the TAP through the appropriate states shown in [Figure 11.14](#).

The states of the data and instruction register scan blocks are mirror images of each other adding symmetry to the protocol sequences. The first action that occurs when either block is entered is a capture operation. For the data registers, the *Capture-DR* state is used to capture (or parallel load) the data into the selected serial data path. In the Instruction register, the *Capture-IR* state is used to capture status information into the Instruction register.

From the *Capture* states, the TAP transitions to either the *Shift* or *Exit1* states. Normally the *Shift* state follows the *Capture* state so that test data or status information can be shifted out for inspection and new data shifted in. Following the *Shift* state, the TAP either returns to the *Run-Test/Idle* state via the *Exit1* and *Update* states or enters the *Pause* state via *Exit1*. The reason for entering the *Pause* state is to temporarily suspend the shifting of data through either the Data or Instruction Register while a required operation, such as refilling a host memory buffer, is performed. From the *Pause* state shifting can resume by re-entering the *Shift* state via the *Exit2* state or terminate by entering the *Run-Test/Idle* state via the *Exit2* and *Update* states.

Upon entering the data or Instruction register scan blocks, shadow latches in the selected scan path are forced to hold their present state during the *Capture* and *Shift* operations. The data being shifted into the selected scan path is not output through the shadow latch until the TAP enters the *Update-DR* or *Update-IR* state. The *Update* state causes the shadow latches to update (or parallel load) with the new data that has been shifted into the selected scan path.

Figure 11.14 TAP Controller State Diagram



11.3.2.1 Test-Logic-Reset State

In the *Test-Logic-Reset* state the boundary scan test logic is disabled. The test logic enters the *Test-Logic-Reset* state when the *TMS* input is held HIGH for at least five rising edges of *TCK*. The *BYPASS* instruction is forced into the instruction register output latches during this state. The controller remains in the *Test-Logic-Reset* state as long as *TMS* is HIGH.

11.3.2.2 Run-Test/Idle State

The controller enters the *Run-Test/Idle* state between scan operations. The controller remains in this state as long as *TMS* is held LOW. The instruction register and all test data registers retain their previous state. The instruction cannot change when the TAP controller is in this state.

When *TMS* is sampled HIGH on the rising edge of *TCK*, the controller transitions to the *Select_DR* state.

11.3.2.3 Select_DR_Scan State

This is a temporary controller state in which all test data registers selected by the current instruction retain their previous state. If *TMS* is sampled LOW at the rising edge of *TCK*, then the controller transitions to the *Capture_DR* state. A HIGH on *TMS* causes the controller to transition to the *Select_IR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.4 Select_IR_Scan State

This is a temporary controller state in which all test data registers selected by the current instruction retain their previous state. If *TMS* is sampled LOW on the rising edge of *TCK*, the controller transitions to the *Capture_IR* state. A HIGH on *TMS* causes the controller to transition to the *Test-Reset-Logic* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.5 Capture_DR State

In this state the boundary scan register captures the value of the register addressed by the Instruction register, and the value is then shifted out in the *Shift_DR*. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Shift_DR* state. A HIGH on *TMS* causes the controller to transition to the *Exit1_DR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.6 Shift_DR State

In this state the test data register connected between *TDI* and *TDO* as a result of the current instruction shifts data one stage toward its serial output on the rising edge of *TCK*. If *TMS* is sampled LOW on the rising edge of *TCK*, the controller remains in the *Shift_DR* state. A HIGH on *TMS* causes the controller to transition to the *Exit1_DR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.7 Exit1_DR State

This is a temporary controller state in which all test data registers selected by the current instruction retain their previous state. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Pause_DR* state. A HIGH on *TMS* causes the controller to transition to the *Update_DR* state which terminates the scanning process. The instruction cannot change while the TAP controller is in this state.

11.3.2.8 Pause_DR State

The *Pause_DR* state allows the controller to temporarily halt the shifting of data through the test data register in the serial path between *TDI* and *TDO*. All test data registers selected by the current instruction retain their previous state. If *TMS* is sampled LOW on the rising edge of *TCK*, the controller remains in the *Pause_DR* state. A HIGH on *TMS* causes the controller to transition to the *Exit2_DR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.9 Exit2_DR State

This is a temporary controller state in which all test data registers selected by the current instruction retain their previous state. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Shift_DR* state to allow another serial shift of data. A HIGH on *TMS* causes the controller to transition to the *Update_DR* state which terminates the scanning process. The instruction cannot change while the TAP controller is in this state.

11.3.2.10 Update_DR State

When the TAP controller is in this state the value shifted in during the *Shift_DR* state takes effect on the rising edge of the *TCK* for the register indicated by the Instruction register.

If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Run-Test/Idle* state. A HIGH on *TMS* causes the controller to transition to the *Select_DR_Scan* state. The instruction cannot change while the TAP controller is in this state and all shift register stages in the test data registers selected by the current instruction retain their previous state.

11.3.2.11 Capture_IR State

In this state the shift register contained in the Instruction register loads a fixed pattern (00001₂) on the rising edge of *TCK*. The data registers selected by the current instruction retain their previous state.

If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Shift_IR* state. A HIGH on *TMS* causes the controller to transition to the *Exit1_IR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.12 Shift_IR State

In this state the instruction register is connected between *TDI* and *TDO* and shifts data one stage toward its serial output on the rising edge of *TCK*. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller remains in the *Shift_IR* state. A HIGH on *TMS* causes the controller to transition to the *Exit1_IR* state.

11.3.2.13 Exit1_IR State

This is a temporary controller state in which all registers retain their previous state. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Pause_IR* state. A HIGH on *TMS* causes the controller to transition to the *Update_IR* state which terminates the scanning process. The instruction cannot change while the TAP controller is in this state and the instruction register retains its previous state.

11.3.2.14 Pause_IR State

The *Pause_IR* state allows the controller to temporarily halt the shifting of data through the instruction register in the serial path between *TDI* and *TDO*. If *TMS* is sampled LOW at the rising edge of *TCK*, the controller remains in the *Pause_IR* state. A HIGH on *TMS* causes the controller to transition to the *Exit2_IR* state. The instruction cannot change while the TAP controller is in this state.

11.3.2.15 Exit2_IR State

This is a temporary controller state in which the instruction register retains its previous state. If *TMS* is sampled LOW at the rising edge of *TCK*, then the controller transitions to the *Shift_IR* state to allow another serial shift of data. A HIGH on *TMS* causes the controller to transition to the *Update_IR* state which terminates the scanning process. The instruction cannot change while the TAP controller is in this state.

11.3.2.16 Update_IR State

The instruction shifted into the instruction register takes effect on the rising edge of *TCK*.

If *TMS* is sampled LOW at the rising edge of *TCK*, the controller transitions to the *Run-Test/Idle* state. A HIGH on *TMS* causes the controller to transition to the *Select_DR_Scan* state.

11.3.3 Test Access Port (TAP) Instructions

The TAP Instruction register allows instructions to be serially input into the device when TAP controller is in the *Shift-IR* state. Instructions are decoded and define the serial test data register path that is used to shift data between *TDI* and *TDO* during data register scanning.

The Instruction register is a 5-bit register. In the current EJTAG implementation only some instructions have been decoded; the unused instructions default to the BYPASS instruction.

Table 11.22 Implemented EJTAG Instructions

| Value | Instruction | Function |
|-------|-------------|---|
| 0x01 | IDCODE | Select Chip Identification data register |
| 0x03 | IMPCODE | Select Implementation register |
| 0x08 | ADDRESS | Select Address register |
| 0x09 | DATA | Select Data register |
| 0x0A | CONTROL | Select EJTAG Control register |
| 0x0B | ALL | Select the Address, Data and EJTAG Control registers |
| 0x0C | EJTAGBOOT | Set EjtagBrk, ProbEn and ProbTrap to 1 as reset value |
| 0x0D | NORMALBOOT | Set EjtagBrk, ProbEn and ProbTrap to 0 as reset value |
| 0x0E | FASTDATA | Selects the Data and Fastdata registers |
| 0x10 | TCBCONTROLA | Selects the <i>TCBTCONTROLA</i> register in the Trace Control Block |
| 0x11 | TCBCONTROLB | Selects the <i>TCBTCONTROLB</i> register in the Trace Control Block |
| 0x12 | TCBDATA | Selects the <i>TCBDATA</i> register in the Trace Control Block |
| 0x13 | TCBCONTROLC | Selects the <i>TCBTCONTROLC</i> register in the Trace Control Block |
| 0x14 | PCSAMPLE | Selects the <i>PCSAMPLE</i> register |
| 0x1F | BYPASS | Bypass mode |

11.3.3.1 BYPASS Instruction

The required BYPASS instruction allows the processor to remain in a functional mode and selects the Bypass register to be connected between *TDI* and *TDO*. The BYPASS instruction allows serial data to be transferred through the processor from *TDI* to *TDO* without affecting its operation. The bit code of this instruction is defined to be all ones by the IEEE 1149.1 standard. Any unused instruction is defaulted to the BYPASS instruction.

11.3.3.2 IDCODE Instruction

The IDCODE instruction allows the processor to remain in its functional mode and selects the Device Identification (ID) register to be connected between *TDI* and *TDO*. The Device ID register is a 32-bit shift register containing information regarding the IC manufacturer, device type, and version code. Accessing the Identification Register does not interfere with the operation of the processor. Also, access to the Identification Register is immediately available, via a TAP data scan operation, after power-up when the TAP has been reset with on-chip power-on or through the optional *TRST_N* pin.

11.3.3.3 IMPCODE Instruction

This instruction selects the Implementation register for output, which is always 32 bits.

11.3.3.4 ADDRESS Instruction

This instruction is used to select the Address register to be connected between *TDI* and *TDO*. The EJTAG Probe shifts 32 bits through the *TDI* pin into the Address register and shifts out the captured address via the *TDO* pin.

11.3.3.5 DATA Instruction

This instruction is used to select the Data register to be connected between *TDI* and *TDO*. The EJTAG Probe shifts 32 bits of *TDI* data into the Data register and shifts out the captured data via the *TDO* pin.

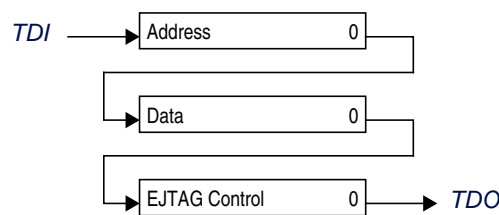
11.3.3.6 CONTROL Instruction

This instruction is used to select the EJTAG Control register to be connected between *TDI* and *TDO*. The EJTAG Probe shifts 32 bits of *TDI* data into the EJTAG Control register and shifts out the EJTAG Control register bits via *TDO*.

11.3.3.7 ALL Instruction

This instruction is used to select the concatenation of the Address and Data register, and the EJTAG Control register (ECR) between *TDI* and *TDO*. It can be used in particular to minimize the overhead in switching the instruction in the instruction register. The first bit shifted out is bit 0 of the ECR.

Figure 11.15 Concatenation of the EJTAG Address, Data and Control Registers



11.3.3.8 EJTAGBOOT Instruction

EJTAGBOOT provides a means to enter debug mode just after a reset, without fetching or executing any instructions from the normal memory area. This can be used for download of code to a system which has no code in ROM.

When the EJTAGBOOT instruction is given and the Update-IR state is left, the EJTAGBOOT indication will become active. When EJTAGBOOT is active, a core reset will set the ProbTrap, ProbEn and EjtagBrk bits in the EJTAG Control register to 1. This will cause a debug exception that is serviced by the probe immediately after reset is deasserted.

This EJTAGBOOT indication is effective until a NORMALBOOT instruction is given, *TRST_N* is asserted or a rising edge of *TCK* occurs when the TAP controller is in Test-Logic-Reset state.

The Bypass register is selected when the EJTAGBOOT instruction is given.

11.3.3.9 NORMALBOOT Instruction

When the NORMALBOOT instruction is given and the Update-IR state is left, then the EJTAGBOOT indication will be cleared. When NORMALBOOT is active (EJTAGBOOT is not active), a core reset will set the ProbTrap, ProbEn and EjtagBrk bits in the EJTAG Control register to 0.

The Bypass register is selected when the NORMALBOOT instruction is given.

11.3.3.10 FASTDATA Instruction

This selects the Data and the Fastdata registers at once, as shown in Figure 11.16.

Figure 11.16 TDI to TDO Path When in Shift-DR State and FASTDATA Instruction is Selected



11.3.3.11 TCBCONTROLA Instruction

This instruction is used to select the TCBCONTROLA register to be connected between *TDI* and *TDO*. This register is only implemented if the Trace Control Block is present. If no TCB is present, then this instruction will select the Bypass register.

11.3.3.12 TCBCONTROLB Instruction

This instruction is used to select the TCBCONTROLB register to be connected between *TDI* and *TDO*. This register is only implemented if the Trace Control Block is present. If no TCB is present, then this instruction will select the Bypass register.

11.3.3.13 TCBCONTROLC Instruction

This instruction is used to select the TCBCONTROLC register to be connected between *TDI* and *TDO*. This register is only implemented if the Trace Control Block is present. If no TCB is present, then this instruction will select the Bypass register.

11.3.3.14 TCBDATA Instruction

This instruction is used to select the TCBDATA register to be connected between *TDI* and *TDO*. This register is only implemented if the Trace Control Block is present. If no TCB is present, then this instruction will select the Bypass register. It should be noted that the TCBDATA register is only an access register to other TCB registers. The width of the TCBDATA register is dependent on the specific TCB register.

11.3.3.15 PCSAMPLE Instruction

This instruction is used to select the PCSAMPLE register to be connected between *TDI* and *TDO*. This register is always implemented.

11.4 EJTAG TAP Registers

The EJTAG TAP Module has one Instruction register and a number of data registers, all accessible through the TAP:

11.4.1 Instruction Register

The Instruction register is accessed when the TAP receives an Instruction register scan protocol. During an Instruction register scan operation the TAP controller selects the output of the Instruction register to drive the *TDO* pin. The shift register consists of a series of bits arranged to form a single scan path between *TDI* and *TDO*. During an Instruction register scan operations, the TAP controls the register to capture status information and shift data from *TDI* to *TDO*. Both the capture and shift operations occur on the rising edge of *TCK*. However, the data shifted out from the *TDO* occurs on the falling edge of *TCK*. In the Test-Logic-Reset and *Capture-IR* state, the instruction shift register is

set to 00001₂, as for the IDCODE instruction. This forces the device into the functional mode and selects the Device ID register. The Instruction register is 5 bits wide. The instruction shifted in takes effect for the following data register scan operation. A list of the implemented instructions are listed in [Table 11.22](#).

11.4.2 Data Registers Overview

The EJTAG uses several data registers, which are arranged in parallel from the primary *TDI* input to the primary *TDO* output. The Instruction register supplies the address that allows one of the data registers to be accessed during a data register scan operation. During a data register scan operation, the addressed scan register receives TAP control signals to capture the register and shift data from *TDI* to *TDO*. During a data register scan operation, the TAP selects the output of the data register to drive the *TDO* pin. The register is updated in the *Update-DR* state with respect to the write bits.

This description applies in general to the following data registers:

- Bypass Register
- Device Identification Register
- Implementation Register
- EJTAG Control Register (ECR)
- Processor Access Address Register
- Processor Access Data Register
- FastData Register

11.4.2.1 Bypass Register

The *Bypass* register consists of a single scan register bit. When selected, the Bypass register provides a single bit scan path between *TDI* and *TDO*. The Bypass register allows abbreviating the scan path through devices that are not involved in the test. The Bypass register is selected when the Instruction register is loaded with a pattern of all ones to satisfy the IEEE 1149.1 Bypass instruction requirement.

11.4.2.2 Device Identification (ID) Register

The *Device Identification* register is defined by IEEE 1149.1, to identify the device's manufacturer, part number, revision, and other device-specific information. [Table 11.23](#) shows the bit assignments defined for the read-only Device Identification Register, and inputs to the core determine the value of these bits. These bits can be scanned out of the *ID* register after being selected. The register is selected when the Instruction register is loaded with the IDCODE instruction.

Figure 11.17 Device Identification Register Format

| | | | | | | |
|---------|----|----|------------|----|---|---------|
| 31 | 28 | 27 | 12 | 11 | 1 | 0 |
| Version | | | PartNumber | | | ManufID |
| | | | | | | R |

Table 11.23 Device Identification Register

| Fields | | Description | Read / Write | Reset State |
|------------|--------|---|--------------|----------------------------|
| Name | Bit(s) | | | |
| Version | 31:28 | Version (4 bits) This field identifies the version number of the processor derivative. | R | <i>EJ_Version[3:0]</i> |
| PartNumber | 27:12 | Part Number (16 bits) This field identifies the part number of the processor derivative. | R | <i>EJ_PartNumber[15:0]</i> |
| ManufID | 11:1 | Manufacturer Identity (11 bits) Accordingly to IEEE 1149.1-1990, the manufacturer identity code shall be a compressed form of the JEDEC Publications 106-A. | R | <i>EJ_ManufID[10:0]</i> |
| R | 0 | reserved | R | 1 |

11.4.2.3 Implementation Register

This 32-bit read-only register is used to identify the features of the EJTAG implementation. Some of the reset values are set by inputs to the core. The register is selected when the Instruction register is loaded with the IMPCODE instruction.

Figure 11.18 Implementation Register Format

| | | | | | | | | | | | | | |
|----------|----------|----|---------|----------|----------|----|--------|----|-------|----------|----|----|---|
| 31 | 29 | 28 | 25 | 24 | 23 | 21 | 20 | 17 | 16 | 15 | 14 | 13 | 0 |
| EJTAGver | reserved | | DINTsup | ASIDsize | reserved | | MIPS16 | 0 | NoDMA | reserved | | | |

Table 11.24 Implementation Register Descriptions

| Fields | | Description | Read / Write | Reset State |
|----------|--------|---|--------------|-------------------------|
| Name | Bit(s) | | | |
| EJTAGver | 31:29 | EJTAG Version. 3: Version 3.1 | R | 3 |
| reserved | 28:25 | reserved | R | 0 |
| DINTsup | 24 | DINT Signal Supported from Probe This bit indicates if the DINT signal from the probe is supported: 0: DINT signal from the probe is not supported 1: Probe can use DINT signal to make debug interrupt. | R | <i>EJ_DINTsup</i> |
| ASIDsize | 23:21 | Size of ASID field in implementation: 0: No ASID in implementation 2: 8-bit ASID 1,3: Reserved | R | TLB MMU- 2 FM MMU- 0 |
| reserved | 20:17 | reserved | R | 0 |
| MIPS16 | 16 | Indicates whether MIPS16 is implemented 0: No MIPS16 support 1: MIPS16 implemented | R | 1 |
| reserved | 15 | reserved | R | 0 |
| NoDMA | 14 | No EJTAG DMA Support | R | 1 |
| reserved | 13:0 | reserved | R | 0 |

11.4.2.4 EJTAG Control Register

This 32-bit register controls the various operations of the TAP modules. This register is selected by shifting in the CONTROL instruction. Bits in the EJTAG Control register can be set/cleared by shifting in data; status is read by shifting out the contents of this register. This EJTAG Control register can only be accessed by the TAP interface.

The EJTAG Control register is not updated in the *Update-DR* state unless the Reset occurred (Rocc) bit 31, is either 0 or written to 0. This is in order to ensure proper handling of processor accesses.

The value used for reset indicated in the table below takes effect on CPU resets, but not on TAP controller resets by e.g. *TRST_N*. *TCK* clock is not required when the CPU reset occurs, but the bits are still updated to the reset value when the *TCK* applies. The first 5 *TCK* clocks after CPU resets may result in reset of the bits, due to synchronization between clock domains.

Figure 11.19 EJTAG Control Register Format

| | | | | | | | | | | | | | | | | | | | | | |
|------|-----|-----|-----|------|------|--------|------|-------|-----|-------|--------|----------|-----|----------|-----|----|-----|---|---|---|---|
| 31 | 30 | 29 | 28 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 4 | 3 | 2 | 0 |
| Rocc | Psz | Res | Res | Doze | Halt | PerRst | PRnW | PrAcc | Res | PrRst | ProbEn | ProbTrap | Res | EjtagBrk | Res | DM | Res | | | | |

Table 11.25 EJTAG Control Register Descriptions

| Fields | | Description | Read / Write | Reset State |
|--------|--------|--|--------------|-------------|
| Name | Bit(s) | | | |
| Rocc | 31 | <p>Reset Occurred</p> <p>The bit indicates if a CPU reset has occurred:</p> <p>0: No reset occurred since bit last cleared.</p> <p>1: Reset occurred since bit last cleared.</p> <p>The Rocc bit will keep the 1 value as long as reset is applied.</p> <p>This bit must be cleared by the probe, t_Ö(knowledge that the incident was detected).</p> <p>The EJTAG Control register is not updated in the <i>Update-DR</i> state unless Rocc is 0, or written to 0. This is in order to ensure proper handling of processor access.</p> | R/W | 1 |

Table 11.25 EJTAG Control Register Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|------------|----------|---|--------------|-------------|---------------|----|----|-------------------------------|----|----|-------------------------------|----|----|-------------------------------|----|----|-------------------------------|----|----|---|----|----|---|----|----|---------------------------------|----|----|---|----|----|---|------------|--|----------|---|-----------|
| Name | Bit(s) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Psz[1:0] | 30:29 | <p>Processor Access Transfer Size</p> <p>These bits are used in combination with the lower two address bits of the Address register to determine the size of a processor access transaction. The bits are only valid when processor access is pending.</p> <table><tr><th>PAA[1:0]</th><th>Psz[1:0]</th><th>Transfer Size</th></tr><tr><td>00</td><td>00</td><td>Byte (LE, byte 0; BE, byte 3)</td></tr><tr><td>01</td><td>00</td><td>Byte (LE, byte 1; BE, byte 2)</td></tr><tr><td>10</td><td>00</td><td>Byte (LE, byte 2; BE, byte 1)</td></tr><tr><td>11</td><td>00</td><td>Byte (LE, byte 3; BE, byte 0)</td></tr><tr><td>00</td><td>01</td><td>Halfword (LE, bytes 1:0; BE, bytes 3:2)</td></tr><tr><td>10</td><td>01</td><td>Halfword (LE, bytes 3:2; BE, bytes 1:0)</td></tr><tr><td>00</td><td>10</td><td>Word (LE, BE; bytes 3, 2, 1, 0)</td></tr><tr><td>00</td><td>11</td><td>Triple (LE, bytes 2, 1, 0; BE, bytes 3, 2, 1)</td></tr><tr><td>01</td><td>11</td><td>Triple (LE, bytes 3, 2, 1; BE, bytes 2, 1, 0)</td></tr><tr><td colspan="2">All others</td><td>Reserved</td></tr></table> <p>Note: LE=little endian, BE=big endian, the byte# refers to the byte number in a 32-bit register, where byte 3 = bits 31:24; byte 2 = bits 23:16; byte 1 = bits 15:8; byte 0=bits 7:0, independently of the endianness.</p> | PAA[1:0] | Psz[1:0] | Transfer Size | 00 | 00 | Byte (LE, byte 0; BE, byte 3) | 01 | 00 | Byte (LE, byte 1; BE, byte 2) | 10 | 00 | Byte (LE, byte 2; BE, byte 1) | 11 | 00 | Byte (LE, byte 3; BE, byte 0) | 00 | 01 | Halfword (LE, bytes 1:0; BE, bytes 3:2) | 10 | 01 | Halfword (LE, bytes 3:2; BE, bytes 1:0) | 00 | 10 | Word (LE, BE; bytes 3, 2, 1, 0) | 00 | 11 | Triple (LE, bytes 2, 1, 0; BE, bytes 3, 2, 1) | 01 | 11 | Triple (LE, bytes 3, 2, 1; BE, bytes 2, 1, 0) | All others | | Reserved | R | Undefined |
| PAA[1:0] | Psz[1:0] | Transfer Size | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00 | 00 | Byte (LE, byte 0; BE, byte 3) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 01 | 00 | Byte (LE, byte 1; BE, byte 2) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | 00 | Byte (LE, byte 2; BE, byte 1) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | 00 | Byte (LE, byte 3; BE, byte 0) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00 | 01 | Halfword (LE, bytes 1:0; BE, bytes 3:2) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | 01 | Halfword (LE, bytes 3:2; BE, bytes 1:0) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00 | 10 | Word (LE, BE; bytes 3, 2, 1, 0) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 00 | 11 | Triple (LE, bytes 2, 1, 0; BE, bytes 3, 2, 1) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 01 | 11 | Triple (LE, bytes 3, 2, 1; BE, bytes 2, 1, 0) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| All others | | Reserved | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Res | 28:24 | reserved | R | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Res | 23 | reserved | R | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Doze | 22 | <p>Doze state</p> <p>The Doze bit indicates any kind of low power mode. The value is sampled in the Capture-DR state of the TAP controller:</p> <p>0: CPU not in low power mode.</p> <p>1: CPU is in low power mode</p> <p>Doze includes the Reduced Power (RP) and WAIT power-reduction modes.</p> | R | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Halt | 21 | <p>Halt state</p> <p>The Halt bit indicates if the internal system bus clock is running or stopped. The value is sampled in the Capture-DR state of the TAP controller:</p> <p>0: Internal system clock is running</p> <p>1: Internal system clock is stopped</p> | R | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Table 11.25 EJTAG Control Register Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| PerRst | 20 | <p>Peripheral Reset</p> <p>When the bit is set to 1, it is only guaranteed that the peripheral reset has occurred in the system when the read value of this bit is also 1. This is to ensure that the setting from the <i>TCK</i> clock domain gets effect in the CPU clock domain, and in peripherals.</p> <p>When the bit is written to 0, then the bit must also be read as 0 before it is guaranteed that the indication is cleared in the CPU clock domain also.</p> <p>This bit controls the <i>EJ_PerRst</i> signal on the core.</p> | R/W | 0 |
| PRnW | 19 | <p>Processor Access Read and Write</p> <p>This bit indicates if the pending processor access is for a read or write transaction, and the bit is only valid while PrAcc is set:</p> <p>0: Read transaction 1: Write transaction</p> | R | Undefined |
| PrAcc | 18 | <p>Processor Access (PA)</p> <p>Read value of this bit indicates if a Processor Access (PA) to the EJTAG memory is pending:</p> <p>0: No pending processor access 1: Pending processor access</p> <p>The probe's software must clear this bit to 0 to indicate the end of the PA. Write of 1 is ignored.</p> <p>A pending Processor Access is cleared when Rocc is set, but another PA may occur just after the reset if a debug exception occurs.</p> <p>Finishing a Processor Access is not accepted while the Rocc bit is set. This is to avoid that a Processor Access occurring after the reset is finished due to indication of a Processor Access that occurred before the reset.</p> <p>The FASTDATA access can clear this bit.</p> | R/W0 | 0 |
| Res | 17 | reserved | R | 0 |
| PrRst | 16 | <p>Processor Reset (Implementation dependent behavior)</p> <p>When the bit is set to 1, then it is only guaranteed that this setting has taken effect in the system when the read value of this bit is also 1. This is to ensure that the setting from the <i>TCK</i> clock domain gets effect in the CPU clock domain, and in peripherals.</p> <p>When the bit is written to 0, then the bit must also be read as 0 before it is guaranteed that the indication is cleared in the CPU clock domain also.</p> <p>This bit controls the <i>EJ_PrRst</i> signal. If the signal is used in the system, then it must be ensured that both the processor and all devices required for a reset are properly reset. Otherwise the system may fail or hang. The bit resets itself, since the <i>EJTAG Control</i> register is reset by a reset.</p> | R/W | 0 |

Table 11.25 EJTAG Control Register Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|----------|--------|--|--------------|-----------------------|
| Name | Bit(s) | | | |
| ProbEn | 15 | <p>Probe Enable</p> <p>This bit indicates to the CPU if the EJTAG memory is handled by the probe so processor accesses are answered:</p> <p>0: The probe does not handle EJTAG memory transactions</p> <p>1: The probe does handle EJTAG memory transactions</p> <p>It is an error by the software controlling the probe if it sets the ProbTrap bit to 1, but resets the ProbEn to 0. The operation of the processor is UNDEFINED in this case.</p> <p>The ProbEn bit is reflected as a read-only bit in the ProbEn bit, bit 0, in the Debug Control Register (DCR).</p> <p>The read value indicates the effective value in the DCR, due to synchronization issues between <i>TCK</i> and CPU clock domains; however, it is ensured that change of the ProbEn prior to setting the EjtagBrk bit will have effect for the debug handler executed due to the debug exception.</p> <p>The reset value of the bit depends on whether the EJTAGBOOT indication is given or not:</p> <p>No EJTAGBOOT indication given: 0</p> <p>EJTAGBOOT indication given: 1</p> | R/W | 0 or 1 from EJTAGBOOT |
| ProbTrap | 14 | <p>Probe Trap</p> <p>This bit controls the location of the debug exception vector:</p> <p>0: In normal memory 0xBFC0.0480</p> <p>1: In EJTAG memory at 0xFF20.0200 in dmseg</p> <p>Valid setting of the ProbTrap bit depends on the setting of the ProbEn bit, see comment under ProbEn bit.</p> <p>The ProbTrap should not be set to 1, for debug exception vector in EJTAG memory, unless the ProbEn bit is also set to 1 to indicate that the EJTAG memory may be accessed.</p> <p>The read value indicates the effective value to the CPU, due to synchronization issues between <i>TCK</i> and CPU clock domains; however, it is ensured that change of the ProbTrap bit prior to setting the EjtagBrk bit will have effect for the EjtagBrk.</p> <p>The reset value of the bit depends on whether the EJTAGBOOT indication is given or not:</p> <p>No EJTAGBOOT indication given: 0</p> <p>EJTAGBOOT indication given: 1</p> | R/W | 0 or 1 from EJTAGBOOT |
| Res | 13 | reserved | R | 0 |
| EjtagBrk | 12 | <p>EJTAG Break</p> <p>Setting this bit to 1 causes a debug exception to the processor, unless the CPU was in debug mode or another debug exception occurred. When the debug exception occurs, the processor core clock is restarted if the CPU was in low power mode. This bit is cleared by hardware when the debug exception is taken.</p> <p>The reset value of the bit depends on whether the EJTAGBOOT indication is given or not:</p> <p>No EJTAGBOOT indication given: 0</p> <p>EJTAGBOOT indication given: 1</p> | R/W | 0 or 1 from EJTAGBOOT |
| Res | 11:4 | reserved | R | 0 |

Table 11.25 EJTAG Control Register Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|--------|---|--------------|-------------|
| Name | Bit(s) | | | |
| DM | 3 | Debug Mode This bit indicates the debug or non-debug mode: 0: Processor is in non-debug mode 1: Processor is in debug mode The bit is sampled in the <i>Capture-DR</i> state of the TAP controller. | R | 0 |
| Res | 2:0 | Reserved | R | 0 |

11.4.3 Processor Access Address Register

The Processor Access Address (*PAA*) register is used to provide the address of the processor access in the dmseg, and the register is only valid when a processor access is pending. The length of the Address register is 32 bits, and this register is selected by shifting in the ADDRESS instruction.

11.4.3.1 Processor Access Data Register

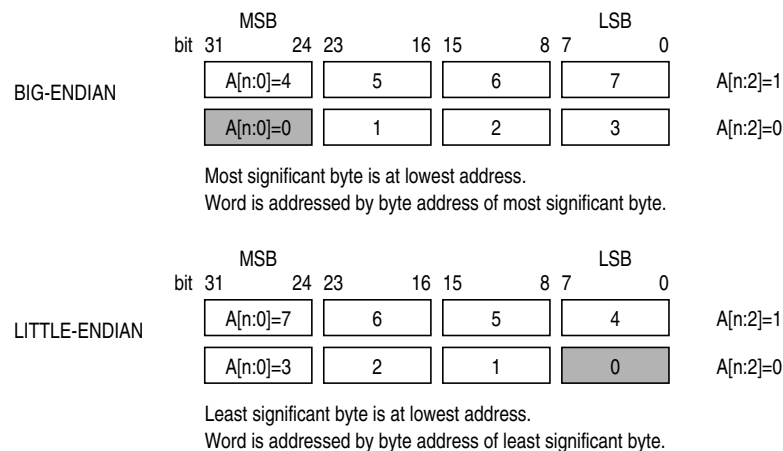
The Processor Access Data (*PAD*) register is used to provide data value to and from a processor access. The length of the Data register is 32 bits, and this register is selected by shifting in the DATA instruction.

The register has the written value for a processor access write due to a CPU store to the dmseg, and the output from this register is only valid when a processor access write is pending. The register is used to provide the data value for a processor access read due to a CPU load or fetch from the dmseg, and the register should only be updated with a new value when a processor access write is pending.

The *PAD* register is 32 bits wide. Data alignment is not used for this register, so the value in the *PAD* register matches data on the internal bus. The undefined bytes for a PA write are undefined, and for a *PAD* read 0 (zero) must be shifted in for the unused bytes.

The organization of bytes in the *PAD* register depends on the endianness of the core, as shown in Figure 11.20. The endian mode for debug/kernel mode is determined by the state of the *SI_Endian* input at power-up.

Figure 11.20 Endian Formats for the PAD Register



The size of the transaction and thus the number of bytes available/required for the *PAD* register is determined by the *Psz* field in the *ECR*.

11.4.4 Fastdata Register (TAP Instruction FASTDATA)

The width of the Fastdata register is 1 bit. During a Fastdata access, the Fastdata register is written and read, i.e., a bit is shifted in and a bit is shifted out. During a Fastdata access, the Fastdata register value shifted in specifies whether the Fastdata access should be completed or not. The value shifted out is a flag that indicates whether the Fastdata access was successful or not (if completion was requested).

Figure 11.21 Fastdata Register Format

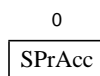


Table 11.26 Fastdata Register Field Description

| Fields | | Description | Read / Write | Power-up State |
|--------|------|---|--------------|----------------|
| Name | Bits | | | |
| SPrAcc | 0 | Shifting in a zero value requests completion of the Fastdata access. The PrAcc bit in the EJTAG Control register is overwritten with zero when the access succeeds. (The access succeeds if PrAcc is one and the operation address is in the legal dmseg Fastdata area.) When successful, a one is shifted out. Shifting out a zero indicates a Fastdata access failure. Shifting in a one does not complete the Fastdata access and the PrAcc bit is unchanged. Shifting out a one indicates that the access would have been successful if allowed to complete and a zero indicates the access would not have successfully completed. | R/W | Undefined |

The FASTDATA access is used for efficient block transfers between dmseg (on the probe) and target memory (on the processor). An “upload” is defined as a sequence of processor loads from target memory and stores to dmseg. A “download” is a sequence of processor loads from dmseg and stores to target memory. The “Fastdata area” specifies the legal range of dmseg addresses (0xFF20.0000 - 0xFF20.000F) that can be used for uploads and downloads. The Data + Fastdata registers (selected with the FASTDATA instruction) allow efficient completion of pending Fastdata area accesses.

During Fastdata uploads and downloads, the processor will stall on accesses to the Fastdata area. The PrAcc (processor access pending bit) will be 1 indicating the probe is required to complete the access. Both upload and download accesses are attempted by shifting in a zero *SPrAcc* value (to request access completion) and shifting out *SPrAcc* to see if the attempt will be successful (i.e., there was an access pending and a legal Fastdata area address was used). Downloads will also shift in the data to be used to satisfy the load from dmseg’s Fastdata area, while uploads will shift out the data being stored to dmseg’s Fastdata area.

As noted above, two conditions must be true for the Fastdata access to succeed. These are:

- *PrAcc* must be 1, i.e., there must be a pending processor access.
- The Fastdata operation must use a valid Fastdata area address in dmseg (0xFF20.0000 to 0xFF20.000F).

Table 11.27 shows the values of the *PrAcc* and *SPrAcc* bits and the results of a Fastdata access. .

Table 11.27 Operation of the FASTDATA Access

| Probe Operation | Address Match Check | PrAcc in the Control Register | LSB (SPrAcc) Shifted In | Action in the Data Register | PrAcc Changes to | Lsb Shifted Out | Data Shifted Out |
|--------------------------|---------------------|-------------------------------|-------------------------|-----------------------------|------------------|-----------------|-----------------------|
| Download using FAST-DATA | Fails | x | x | none | unchanged | 0 | invalid |
| | Passes | 1 | 1 | none | unchanged | 1 | invalid |
| | | 1 | 0 | write data | 0 (SPrAcc) | 1 | valid (previous) data |
| | | 0 | x | none | unchanged | 0 | invalid |
| Upload using FASTDATA | Fails | x | x | none | unchanged | 0 | invalid |
| | Passes | 1 | 1 | none | unchanged | 1 | invalid |
| | | 1 | 0 | read data | 0 (SPrAcc) | 1 | valid data |
| | | 0 | x | none | unchanged | 0 | invalid |

There is no restriction on the contents of the Data register. It is expected that the transfer size is negotiated between the download/upload transfer code and the probe software. Note that the most efficient transfer size is a 32-bit word.

The Rocc bit of the Control register is not used for the FASTDATA operation.

11.5 TAP Processor Accesses

The TAP modules support handling of fetches, loads and stores from the CPU through the dmseg segment, whereby the TAP module can operate like a *slave unit* connected to the on-chip bus. The core can then execute code taken from the EJTAG Probe and it can access data (via a load or store) which is located on the EJTAG Probe. This occurs in a serial way through the EJTAG interface: the core can thus execute instructions e.g. debug monitor code, without occupying the memory.

Accessing the dmseg segment (EJTAG memory) can only occur when the processor accesses an address in the range from 0xFF20.0000 to 0xFF2F.FFFF, the ProbEn bit is set, and the processor is in debug mode (DM=1). In addition the LSNM bit in the CP0 Debug register controls transactions to/from the dmseg.

When a debug exception is taken, while the ProbTrap bit is set, the processor will start fetching instructions from address 0xFF20.0200.

A pending processor access can only finish if the probe writes 0 to PrAcc or by a reset.

11.5.1 Fetch/Load and Store From/To the EJTAG Probe Through dmseg

1. The internal hardware latches the requested address into the PA Address register (in case of the Debug exception: 0xFF20.0200).
2. The internal hardware sets the following bits in the EJTAG Control register:
PrAcc = 1 (selects Processor Access operation)

PRnW = 0 (selects processor read operation)
Psz[1:0] = value depending on the transfer size

3. The EJTAG Probe selects the EJTAG Control register, shifts out this control register's data and tests the PrAcc status bit (Processor Access): when the PrAcc bit is found 1, it means that the requested address is available and can be shifted out.
4. The EJTAG Probe checks the PRnW bit to determine the required access.
5. The EJTAG Probe selects the PA Address register and shifts out the requested address.
6. The EJTAG Probe selects the PA Data register and shifts in the instruction corresponding to this address.
7. The EJTAG Probe selects the EJTAG Control register and shifts a PrAcc = 0 bit into this register to indicate to the processor that the instruction is available.
8. The instruction becomes available in the instruction register and the processor starts executing.
9. The processor increments the program counter and outputs an instruction read request for the next instruction. This starts the whole sequence again.

Using the same protocol, the processor can also execute a load instruction to access the EJTAG Probe's memory. For this to happen, the processor must execute a load instruction (e.g. a LW, LH, LB) with the target address in the appropriate range.

Almost the same protocol is used to execute a store instruction to the EJTAG Probe's memory through dmseg. The store address must be in the range: 0xFF20.0000 to 0xFF2F.FFFF, the ProbEn bit must be set and the processor has to be in debug mode (DM=1). The sequence of actions is found below:

1. The internal hardware latches the requested address into the PA Address register
2. The internal hardware latches the data to be written into the PA Data register.
3. The internal hardware sets the following bits in the EJTAG Control register:
PrAcc = 1 (selects Processor Access operation)
PRnW = 1 (selects processor write operation)
Psz[1:0] = value depending on the transfer size
4. The EJTAG Probe selects the EJTAG Control register, shifts out this control register's data and tests the PrAcc status bit (Processor Access): when the PrAcc bit is found 1, it means that the requested address is available and can be shifted out.
5. The EJTAG Probe checks the PRnW bit to determine the required access.
6. The EJTAG Probe selects the PA Address register and shifts out the requested address.
7. The EJTAG Probe selects the PA Data register and shifts out the data to be written.
8. The EJTAG Probe selects the EJTAG Control register and shifts a PrAcc = 0 bit into this register to indicate to the processor that the write access is finished.
9. The EJTAG Probe writes the data to the requested address in its memory.

10. The processor detects that PrAcc bit = 0, which means that it is ready to handle a new access.

The above examples imply that no reset occurs during the operations, and that Rocc is cleared.

11.6 PC Sampling

The PC sampling feature enables sampling of the PC value periodically. This information can be used for statistical profiling of the program akin to gprof. This information is also very useful for detecting hot-spots in the code. PC sampling cannot be turned on or off, that is, the PC value is continually sampled.

The presence or absence of the PC Sampling feature is available in the Debug Control register as bit 9(PCS). The sampled PC values are written into a TAP register. The old value in the TAP register is overwritten by a new value even if this register has not been read out by the debug probe. The sample rate is specified in a manner similar to the PDtrace synchronization period, with three bits. These bits in the Debug Control register are 8:6 and called PCSR (PC Sample Rate). These three bits take the value 2^5 to 2^{12} similar to SyncPeriod. Note that the processor samples PC even when it is asleep, that is, in a WAIT state. This permits an analysis of the amount of time spent by a processor in WAIT state which may be used for example to revert to a low power mode during the non-execution phase of a real-time application.

The sampled values include a new data bit, the PC, the ASID of the sampled PC as well as the Thread Context id if the processor implements the MIPS MT ASE. Figure shows the format of the sampled values in the TAP register PCsample. The new data bit is used by the probe to determine if the PCsample register data just read out is new or already been read and must be discarded.

Figure 11.22 TAP Register PCsample Format

| | | | | | | |
|----------------------------------|----|------|----|----|---|-----|
| 48 | 41 | 40 | 33 | 32 | 1 | 0 |
| TC (for MIPS MT processors only) | | ASID | | PC | | New |

The sampled PC value is the PC of the graduating instruction in the current cycle. If the processor is stalled when the PC sample counter overflows, then the sampled PC is the PC of the next graduating instruction. The processor continues to sample the PC value even when it is in Debug mode.

11.6.1 PC Sampling in Wait State

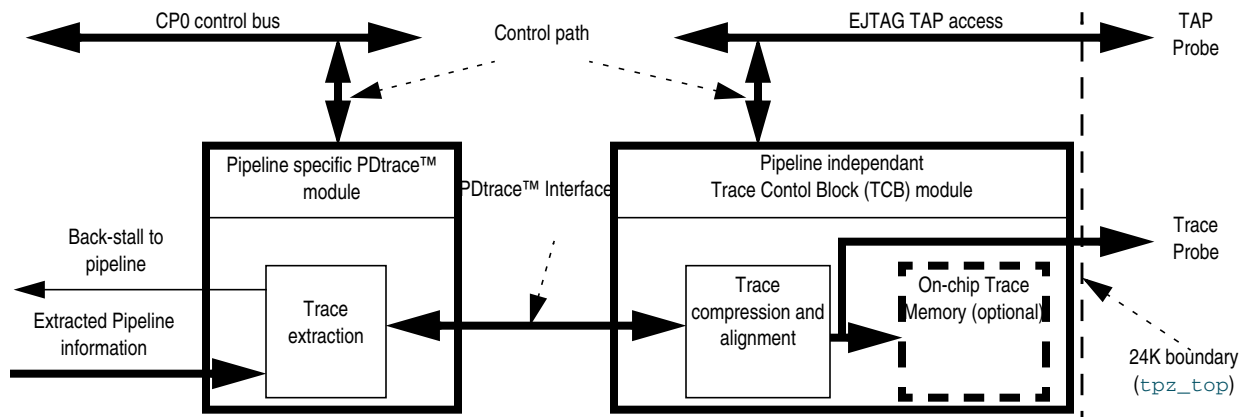
When the processor is in a WAIT state to save power for example, an external agent might want to know how long it stays in the WAIT state. But counting cycles to update the PC sample value is a waste of power. Hence, when in a WAIT state, the processor must simply switch the New bit to 1 every time it is set to 0 by the probe hardware. Hence, the external agent or probe reading the PC value will detect a WAIT instruction for as long as the processor remains in the WAIT state. When the processor leaves the WAIT state, then counting is resumed as before.

11.7 MIPS® Trace

MIPS Trace enables the ability to trace program flow, load/store addresses and load/store data. Several run-time options exist for the level of information which is traced, including tracing only when in specific processor modes (e.g., UserMode or KernelMode). MIPS Trace is an optional block in the 24K core. If MIPS Trace is not implemented, the rest of this chapter is irrelevant. If MIPS Trace is implemented, the *CP0 Config3_{TL}* bit is set.

There are two primary blocks involved in the MIPS Trace solution. The pipeline specific part of MIPS Trace is called the PDtrace module. It extracts the trace information from the processor pipeline, and presents it to a pipeline-independent module called the Trace Control Block (TCB). The TCB and the interface between the two blocks (PDtrace interface) are described in The PDtrace™ Interface and Trace Control Block Specification [9]. While working closely together, the two parts of MIPS Trace are controlled separately by software. Figure 11.23 shows an overview of the MIPS Trace modules within the core.

Figure 11.23 MIPS® Trace Modules in the 24K® Core



To some extent, the two modules both provide similar trace control features, but the access to these features is quite different. The PDtrace controls can only be reached through access to CP0 registers. The TCB controls can only be reached through EJTAG TAP access. The TCB can then control what is traced through the PDtrace™ Interface.

Before describing the MIPS Trace implemented in the 24K core, some common terminology and basic features are explained. The remaining sections of this chapter will then provide a more thorough explanation.

11.7.1 Processor Modes

Tracing can be enabled or disabled based on various processor modes. This section precisely describes these modes. The terminology is then used elsewhere in the document.

```

DebugMode ← (DebugDM = 1)
ExceptionMode ← (not DebugMode) and ((StatusEXL = 1) or (StatusERL = 1))
KernelMode ← (not (DebugMode or ExceptionMode)) and (StatusKSU = 2#00)
SupervisorMode ← (not (DebugMode or ExceptionMode)) and (StatusKSU = 2#01)
UserMode ← (not (DebugMode or ExceptionMode)) and (StatusKSU = 2#10)

```

11.7.2 Software Versus Hardware Control

In some of the specifications and in this text, the terms “software control” and “hardware control” are used to refer to the method for how trace is controlled. Software control is when the CP0 register *TraceControl* is used to select the modes to trace, etc. Hardware control is when the EJTAG register *TCBCTRL0LA* in the TCB, via the PDtrace interface, is used to select the trace modes. The *TraceControl_{TS}* bit determines whether software or hardware control is active. Even in Software control mode, Trace logic will need TCK to toggle atleast once before it is turned on. It is assumed that EJTAG probe will be connected while using Trace and probe reset sequence would toggle TCK. In order to extract Trace data out of TCB, *TCBCTRL0LB.En* should be set to 1 even in “software control” mode.

11.7.3 Trace Information

The main object of trace is to show the exact program flow from a specific program execution or just a small window of the execution. In MIPS Trace this is done by providing the minimal cycle-by-cycle information necessary on the PDtrace™ interface for trace regeneration software to reproduce the trace. The following is a summary of the type of information traced:

- Only instructions which complete at the end of the pipeline are traced, and indicated with a completion-flag. The PC is implicitly pointing to the next instruction.
- Load instructions are indicated with a load-flag.
- Store instructions are indicated with a store-flag¹.
- Taken branches are indicated with a branch-taken-flag on the target instruction.
- New PC information for a branch is only traced if the branch target is unpredictable from the static program image.
- When branch targets are unpredictable, only the delta value from current PC is traced, if it is dynamically determined to reduce the number of bits necessary to indicate the new PC. Otherwise the full PC value is traced.
- When a completing instruction is executed in a different processor mode from the previous one, the new processor mode is traced.
- The first instruction is always traced as a branch target, with processor mode and full PC.
- Periodic synchronization instructions are identified with a sync-flag, and traced with the processor mode and full PC.

All the instruction flags above are combined into one 3-bit value, to minimize the bit information to trace. The possible processor modes are explained in [Section 11.7.1 “Processor Modes”](#).

The target address is statically predictable for all branch and all jump-immediate instructions. If the branch is taken, then the branch-taken-flag will indicate this. All jump-register instructions and ERET/DERET are instructions which have an unpredictable target address. These will have full/delta PC values included in the trace information. Also treated as unpredictable are PC changes which occur due to exceptions, such as an interrupt, reset, etc.

Trace regeneration software is required to know the static program image in memory, in order to reproduce the dynamic flow with the above information. But this is usually not a problem. Only the virtual value of the PC is used. Physical memory location will typically differ.

It is possible to turn on PC delta/full information for all branches, but this should not normally be necessary. As a safety check for trace regeneration software, a periodic synchronization with a full PC is sent. The period of this synchronization is cycle based and programmable.

1. A SC (Store Conditional) instruction is not flagged as a store instruction if the load-locked bit prevented the actual store.

11.7.4 Load/Store Address and Data Trace Information

In addition to PC flow, it is possible to get information on the load/store addresses, as well as the data read/written. When enabled, the following information is optionally added to the trace.

- When load-address tracing is on, the full load address of the first load instruction is traced (indicated by the load-flag). For subsequent loads, a dynamically-determined delta to the previous load address is traced to compress the information which must be sent.
- When store-address tracing is on, the full store address of the first store instruction is traced (indicated by the store-flag). For subsequent stores, a dynamically-determined delta to the previous store address is traced.
- When load-data tracing is on, the full load data read by each load instruction is traced (indicated by the load-flag). Only actual read bytes are traced.
- When store-data tracing is on, the full store data written by each store instruction is traced (indicated by the store-flag). Only written bytes are traced.

After each synchronization instruction, the first load address and the first store address following this are both traced with the full address if load/store address tracing is enabled.

11.7.5 Programmable Processor Trace Mode Options

To enable tracing, a global Trace On signal must be set. When trace is on, it is possible to enable tracing in any combination of the processor modes described in [Section 11.7.1 “Processor Modes”](#). In addition to this, trace can be turned on globally for all process, or only for specific processes by tracing only specific masked values of the ASID found in *EntryHi*_{ASID}.

Additionally, an EJTAG Simple Break trigger point can override the processor mode and ASID selection and turn them all on. Another trigger point can disable this override again.

11.7.6 Programmable Trace Information Options

The processor mode changes are always traced:

- On the first instruction.
- On any synchronization instruction.
- When the mode changes and either the previous or the current processor mode is selected for trace.

The amount of extra information traced is programmable to include:

- PC information only.
- PC and cross product of load/store address/data

If the full internal state of the processor is known prior to trace start, PC and load data are the only information needed to recreate all register values on an instruction by instruction basis.

11.7.6.1 User Data Trace

In addition to the above, a special CP0 register, *UserTraceData*, can generate a data trace. When this register is written, and the global Trace On is set, then the 32-bit data written is put in the trace as special User Data information.

Remark: The User Data is sent even if the processor is operating in an un-traced processor mode.

11.7.7 Enable Trace to Probe On-chip Memory

When trace is On, based on the options listed in [Section 11.7.5 “Programmable Processor Trace Mode Options”](#), the trace information is continuously sent on the PDtrace™ interface to the TCB. The TCB must, however, be enabled to transmit the trace information to the Trace probe or to on-chip trace memory, by having the *TCBCONTROLB_{EN}* bit set. It is possible to enable and disable the TCB in two ways:

- Set/clear the *TCBCONTROLB_{EN}* bit via an EJTAG TAP operation.
- Initialize a TCB trigger to set/clear the *TCBCONTROLB_{EN}* bit.

11.7.8 TCB Trigger

The TCB can optionally include 0 to 8 triggers. A TCB trigger can be programmed to fire from any combination of:

- Probe Trigger Input to the TCB.
- Chip-level Trigger Input to the TCB.
- Processor entry into DebugMode.

When a trigger fires it can be programmed to have any combination of actions:

- Create Probe Trigger Output from TCB.
- Create Chip-level Trigger Output from TCB.
- Set, clear, or start countdown to clear the *TCBCONTROLB_{EN}* bit (start/end/about trigger).
- Put an information byte into the trace stream.

11.7.9 Cycle-by-Cycle Information

All of the trace information listed in [Section 11.7.3 “Trace Information”](#) and [Section 11.7.4 “Load/Store Address and Data Trace Information”](#), will be collected from the PDtrace™ interface by the TCB. The trace will then be compressed and aligned to fit in 64 bit trace words, with no loss of information. It is possible to exclude/include the exact cycle-by-cycle relationship between each instruction. If excluded, the number of bits required in the trace information from the TCB is reduced, and each trace word will only contain information from completing instructions.

11.7.10 Instruction and Data Cache Miss Tracing

It is possible to embed information about Instruction and/or Data cache misses into the trace. There are limitations in the core’s ability to track this and put useful information into the trace.

For the instruction cache miss indicator

- The instruction cache miss indicator is based on whether the instruction is pulled from the cache or the fill buffer. On a cache miss, the fetch is restarted when the data comes back from the BIU and the instructions will come from the Fill Buffer. The miss flag is only set for the first fetch that hits out of the FB to avoid marking every fetch from the line a miss. However, two instructions can be fetched per cycle and both will be marked as a miss. If branching to the middle of a dword though, only 1 miss will be seen.
- The IFU can prefetch down a speculative path which might not be immediately executed. These speculative fetches are filled into the cache. Subsequently, when the code accesses the same address, it is possible that the instruction will hit in the cache even if that instruction was being executed for the very first time.

For the data cache miss indicator:

- The ALU and LSU pipelines can run out of sync with each other. PDtrace instruction capture is done at the end of the ALU pipe, but if the LSU pipe had been stalled, the cache miss info will not yet be known. Thus, this miss indicator is instead sent with the data value.
- For loads, this allows an accurate miss indication as the miss state must be resolved before we have the data.
- This does not help for stores though as the store data value is captured with the instruction execution

11.7.11 Trace Message Format

The TCB collects trace information every cycle from the PDtrace™ interface. This information is collected into six different Trace Formats (TF1 to TF6). One important feature is that all Trace Formats have at least one non-zero bit.

11.7.12 Trace Word Format

After the PDtrace data has been converted into Trace Formats, the trace information must be streamed to either on-chip trace memory or to the trace probe. Each of the major Trace Formats are of different size. This complicates how to store this information into an on-chip memory of fixed width without too much wasted space. It also complicates how to transmit data through a fixed-width trace probe interface to off-chip memory. To minimize memory overhead and or bandwidth-loss, the Trace Formats are collected into Trace Words of fixed width.

A Trace Word (TW) is defined to be 64 bits wide. An empty/invalid TW is built of all zeros. A TW which contains one or more valid TF's is guaranteed to have a non-zero value on one of the four least significant bits [3:0]. During operation of the TCB, each TW is built from the TF's generated each clock cycle. When all 64 bits are used, the TW is full and can be sent to either on-chip trace memory or to the trace probe.

11.8 PDtrace™ Registers (Software Control)

The CP0 registers associated with PDtrace are listed in [Table 11.28](#) and described in [Chapter 6, “CP0 Registers of the 24K® Core” on page 146](#)

Table 11.28 A List of Coprocessor 0 Trace Registers

| Register Number | Sel | Register Name | Reference |
|-----------------|-----|---------------|---|
| 23 | 1 | TraceControl | Section 6.2.29 “Trace Control Register (CP0 Register 23, Select 1)” |

Table 11.28 A List of Coprocessor 0 Trace Registers (Continued)

| Register Number | Sel | Register Name | Reference |
|-----------------|-----|---------------|---|
| 23 | 2 | TraceControl2 | Section 6.2.30 “Trace Control2 Register (CP0 Register 23, Select 2)” |
| 23 | 3 | UserTraceData | Section 6.2.31 “User Trace Data Register (CP0 Register 23, Select 3)” |
| 23 | 4 | TraceBPC | Section 6.2.32 “TraceIBPC Register (CP0 Register 23, Select 4)” |

11.9 Trace Control Block (TCB) Registers (Hardware Control)

The TCB registers used to control its operation are listed in [Table 11.29](#) and [Table 11.30](#). These registers are accessed via the EJTAG TAP interface.

Table 11.29 TCB EJTAG Registers

| EJTAG Register | Name | Description | Implemented |
|----------------|-------------|--|-------------|
| 0x10 | TCBCONTROLA | Control register in the TCB mainly used for controlling the trace input signals to the core on the PDtrace interface. See Section 11.9.1 “TCBCONTROLA Register” . | Yes |
| 0x11 | TCBCONTROLB | Control register in the TCB that is mainly used to specify what to do with the trace information. The <i>REG</i> [25:21] field in this register specifies the number of the TCB internal register accessed by the <i>TCBDATA</i> register. A list of all the registers that can be accessed by the <i>TCBDATA</i> register is shown in Table 11.30 . See Section 11.9.2 “TCBCONTROLB Register” . | Yes |
| 0x12 | TCBDATA | This is used to access registers specified by the <i>REG</i> field in the <i>TCBCONTROLB</i> register. See Section 11.9.3 “TCBDATA Register” . | Yes |
| 0x13 | TCBCONTROLC | Control Register in the TCB used to control and hold tracing information. See Section 11.9.4 “TCBCONTROLC Register” . | Yes |

Table 11.30 Registers Selected by TCBCONTROLB_{REG}

| <i>TCBCONTROLB</i> _{REG} field | Name | Reference | Implemented |
|---|-----------|---|--|
| 0 | TCBCONFIG | Section 11.9.5 “TCBCONFIG Register (Reg 0)” | Yes |
| 4 | TCBTW | Section 11.9.6 “TCBTW Register (Reg 4)” | Yes if on-chip memory exists. Otherwise No |
| 5 | TCBRDP | Section 11.9.7 “TCBRDP Register (Reg 5)” | |
| 6 | TCBWRP | Section 11.9.8 “TCBWRP Register (Reg 6)” | |
| 7 | TCBSTP | Section 11.9.9 “TCBSTP Register (Reg 7)” | |
| 16-23 | TCBTRIGx | Section 11.9.10 “TCBTRIGx Register (Reg 16-23)” | Only the number indicated by <i>TCBCONFIG</i> _{TRIG} are implemented. |

11.9.1 TCBCONTROLA Register

The TCB is responsible for asserting or de-asserting the trace input control signals on the PDtrace interface to the core’s tracing logic. Most of the control is done using the *TCBCONTROLA* register.

The *TCBCONTROLA* register is written by an EJTAG TAP controller instruction, TCBCONTROLA (0x10).

The format of the *TCBCONTROLA* register is shown below, and the fields are described in Table 11.31.

Figure 11.24 TCBCONTROLA Register Format

| | | | | | | | | | | | | | | | | | | | | |
|----|--------|-----|-----|----|----|----|----|----|----|----|------|----|------|------|-----|----|---|---|---|---|
| 31 | 26 | 25 | 24 | 23 | 22 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0 | VModes | ADW | SyP | TB | IO | D | E | S | K | U | ASID | G | TFCR | TLSM | TIM | On | | | | |

Table 11.31 TCBCONTROLA Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | |
|----------|--|---|--------------|-------------|-----|-----------------|-----|--|-----|--|-----|----------------|-----|----------------|-----|-----------------|-----|-----------------|-----|-----------------|-----|-----|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | |
| 0 | 31:26 | Reserved. Must be written as zero; returns zero on read. | R | 0 | | | | | | | | | | | | | | | | | | |
| VModes | 25:24 | <div>This field specifies the type of tracing that is supported by the processor, as follows:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>00</td><td>PC tracing only</td></tr><tr><td>01</td><td>PC and Load and store address tracing only</td></tr><tr><td>10</td><td>PC, load and store address, and load and store data.</td></tr><tr><td>11</td><td>Reserved</td></tr></table></div> <div>This field is preset to the value of <i>PDO_ValidModes</i>.</div> | Encoding | Meaning | 00 | PC tracing only | 01 | PC and Load and store address tracing only | 10 | PC, load and store address, and load and store data. | 11 | Reserved | R | 10 | | | | | | | | |
| Encoding | Meaning | | | | | | | | | | | | | | | | | | | | | |
| 00 | PC tracing only | | | | | | | | | | | | | | | | | | | | | |
| 01 | PC and Load and store address tracing only | | | | | | | | | | | | | | | | | | | | | |
| 10 | PC, load and store address, and load and store data. | | | | | | | | | | | | | | | | | | | | | |
| 11 | Reserved | | | | | | | | | | | | | | | | | | | | | |
| ADW | 23 | <i>PDO_AD</i> bus width. 0: The <i>PDO_AD</i> bus is 16 bits wide. 1: The <i>PDO_AD</i> bus is 32 bits wide. | R | 1 | | | | | | | | | | | | | | | | | | |
| SyP | 22:20 | <div>Used to indicate the synchronization period. The period (in cycles) between which the periodic synchronization information is to be sent is defined as shown in the table below.<table><tr><th>SyP</th><th>Sync Period</th></tr><tr><td>000</td><td>2⁵</td></tr><tr><td>001</td><td>2⁶</td></tr><tr><td>010</td><td>2⁷</td></tr><tr><td>011</td><td>2⁸</td></tr><tr><td>100</td><td>2⁹</td></tr><tr><td>101</td><td>2¹⁰</td></tr><tr><td>110</td><td>2¹¹</td></tr><tr><td>111</td><td>2¹²</td></tr></table></div> <div>This field defines the value on the <i>PDI_SyncPeriod</i> signal.</div> | SyP | Sync Period | 000 | 2 ⁵ | 001 | 2 ⁶ | 010 | 2 ⁷ | 011 | 2 ⁸ | 100 | 2 ⁹ | 101 | 2 ¹⁰ | 110 | 2 ¹¹ | 111 | 2 ¹² | R/W | 000 |
| SyP | Sync Period | | | | | | | | | | | | | | | | | | | | | |
| 000 | 2 ⁵ | | | | | | | | | | | | | | | | | | | | | |
| 001 | 2 ⁶ | | | | | | | | | | | | | | | | | | | | | |
| 010 | 2 ⁷ | | | | | | | | | | | | | | | | | | | | | |
| 011 | 2 ⁸ | | | | | | | | | | | | | | | | | | | | | |
| 100 | 2 ⁹ | | | | | | | | | | | | | | | | | | | | | |
| 101 | 2 ¹⁰ | | | | | | | | | | | | | | | | | | | | | |
| 110 | 2 ¹¹ | | | | | | | | | | | | | | | | | | | | | |
| 111 | 2 ¹² | | | | | | | | | | | | | | | | | | | | | |
| TB | 19 | Trace All Branches. When set to one, this field indicates that the core must trace either full or incremental PC values for all branches. When set to zero, only the unpredictable branches are traced. This field defines the value on the <i>PDI_TraceAllBranch</i> signal. | R/W | Undefined | | | | | | | | | | | | | | | | | | |

Table 11.31 TCBCONTROLA Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| IO | 18 | Inhibit Overflow. This bit is used to indicate to the core trace logic that slow but complete tracing is desired. Hence, the core tracing logic must not allow a FIFO overflow and discard trace data. This is achieved by stalling the pipeline when the FIFO is nearly full so that no trace records are ever lost. This field defines the value on the <i>PDI_InhibitOverflow</i> signal. | R/W | Undefined |
| D | 17 | When set to one, this enables tracing in Debug mode, i.e., when the <i>DM</i> bit is one in the <i>Debug</i> register. For trace to be enabled in Debug mode, the <i>On</i> bit must be one, and either the <i>G</i> bit must be one, or the current process must match the <i>ASID</i> field in this register. When set to zero, trace is disabled in Debug mode, irrespective of other bits. This field defines the value on the <i>PDI_DM</i> signal. | R/W | Undefined |
| E | 16 | This controls when tracing is enabled. When set, tracing is enabled when either of the <i>EXL</i> or <i>ERL</i> bits in the <i>Status</i> register is one, provided that the <i>On</i> bit (bit 0) is also set, and either the <i>G</i> bit is set, or the current process <i>ASID</i> matches the <i>ASID</i> field in this register. This field defines the value on the <i>PDI_E</i> signal. | R/W | Undefined |
| S | 15 | When set, this enables tracing when the core is in Supervisor mode as defined in the MIPS32 or MIPS64 architecture specification. This is provided the <i>On</i> bit (bit 0) is also set, and either the <i>G</i> bit is set, or the current process <i>ASID</i> matches the <i>ASID</i> field in this register. This field defines the value on the <i>PDI_S</i> signal. | R/W | Undefined |
| K | 14 | When set, this enables tracing when the <i>On</i> bit is set and the core is in Kernel mode. Unlike the usual definition of Kernel Mode, this bit enables tracing only when the <i>ERL</i> and <i>EXL</i> bits in the <i>Status</i> register are zero. This is provided the <i>On</i> bit (bit 0) is also set, and either the <i>G</i> bit is set, or the current process <i>ASID</i> matches the <i>ASID</i> field in this register. This field defines the value on the <i>PDI_K</i> signal. | R/W | Undefined |
| U | 13 | When set, this enables tracing when the core is in User mode as defined in the MIPS32 or MIPS64 architecture specification. This is provided the <i>On</i> bit (bit 0) is also set, and either the <i>G</i> bit is set, or the current process <i>ASID</i> matches the <i>ASID</i> field in this register. This field defines the value on the <i>PDI_U</i> signal. | R/W | Undefined |
| ASID | 12:5 | The <i>ASID</i> field to match when the <i>G</i> bit is zero. When the <i>G</i> bit is one, this field is ignored. This field defines the value on the <i>PDI_ASID</i> signal. | R/W | Undefined |
| G | 4 | When set, this implies that tracing is to be enabled for all processes, provided that other enabling functions (like U, S, etc.,) are also true. This field defines the value on the <i>PDI_G</i> signal. | R/W | Undefined |
| TFCR | 3 | When set, this indicates to the PDtrace interface that complete information about instruction if it can be a function call or return should be traced, that is signal <i>PDI_TraceFuncCR</i> is asserted as long as this value is set to 1. It also indicates to the TCB that the optional <i>Fcr</i> bit must be traced in the appropriate trace formats | R/W | Undefined |

Table 11.31 TCBCONTROLA Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| TLSM | 2 | When set, this indicates to the PDtrace interface that complete information about Load and Store data cache miss should be traced, that is signal <i>PDI_TraceLSMiss</i> is asserted as long as this value is set to 1. It also indicates to the TCB that the optional LSm bit must be traced in the appropriate trace formats. | R/W | Undefined |
| TIM | 1 | When set, this indicates to the PDtrace interface that complete information about instruction cache miss should be traced, that is signal <i>PDI_TraceIMiss</i> is asserted as long as this value is set to 1. It also indicates to the TCB that the optional Im bit must be traced in the appropriate trace formats. | R/W | Undefined |
| On | 0 | This is the global trace enable switch to the core. When zero, tracing from the core is always disabled, unless enabled by core internal software override of the <i>PDI_*</i> input pins. When set to one, tracing is enabled whenever the other enabling functions are also true. This field defines the value on the <i>PDI_TraceOn</i> signal. | R/W | 0 |

11.9.2 TCBCONTROLB Register

The TCB includes a second control register, *TCBCONTROLB* (0x11). This register generally controls what to do with the trace information received.

The format of the *TCBCONTROLB* register is shown below, and the fields are described in Table 11.32.

Figure 11.25 TCBCONTROLB Register Format

| | | | | | | | | | | | | | | | | | | | | | | | |
|----|----|------------|----|----|-----|----|----|----|----|----|----|--------|----|-----|----------|----|-----|----|---|---|---|---|---|
| 31 | 30 | 28 | 27 | 26 | 25 | 21 | 20 | 19 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 8 | 7 | 6 | 3 | 2 | 1 | 0 |
| WE | 0 | TWSrcWidth | | | REG | WR | 0 | RM | TR | BF | TM | TLISIF | CR | Cal | TWSrcVal | CA | OfC | EN | | | | | |

Table 11.32 TCBCONTROLB Register Field Descriptions

| Fields | | Description | Read / Write | Reset State |
|-------------|-------|---|--------------|-------------|
| Name | Bits | | | |
| WE | 31 | Write Enable. Only when set to 1 will the other bits be written in <i>TCBCONTROLB</i> . This bit will always read 0. | R | 0 |
| 0 | 30:28 | Reserved. Must be written as zero; returns zero on read. | R | 0 |
| TWSrc-Width | 27:26 | Used to indicate the number of bits used in the source field of the Trace Word, this is a configuration option of the core that cannot be modified by software. 00 - zero source field width 01 - two bit source field width 10 - four bit source field width 11 - reserved for future use This field can either be 00 or 01 for the 24K core. | R | Preset |
| REG | 25:21 | Register select: This field select the registers accessible through the <i>TCBDATA</i> register. Legal values are shown in Table 11.30. | R/W | 0 |

Table 11.32 TCBCONTROLB Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|--------|------------|---|--------------|-------------|----|----------|----|------------|----|----------|----|----------|-----|---|
| Name | Bits | | | | | | | | | | | | | |
| WR | 20 | Write Registers: When set, the register selected by REG field is read and written when <i>TCBDATA</i> is accessed. Otherwise the selected register is only read. | R/W | 0 | | | | | | | | | | |
| 0 | 19:17 | Reserved. Must be written as zero; returns zero on read. | R | 0 | | | | | | | | | | |
| RM | 16 | Read on-chip trace memory. When written to 1, the read address-pointer of the on-chip memory is set to point to the oldest memory location written since the last reset of pointers. Subsequent access to the <i>TCBTW</i> register (through the <i>TCBDATA</i> register), will automatically increment the read pointer (<i>TCBRDP</i> register) after each read. [Note: The read pointer does not auto-increment if the <i>WR</i> field is one.] When the write pointer is reached, this bit is automatically reset to 0, and the <i>TCBTW</i> register will read all zeros. Once set to 1, writing 1 again will have no effect. The bit is reset by setting the <i>TR</i> bit or by reading the last Trace word in <i>TCBTW</i> . This bit is reserved if on-chip memory is not implemented. | R/W1 | 0 | | | | | | | | | | |
| TR | 15 | Trace memory reset. When written to one, the address pointers for the on-chip trace memory are reset to zero. Also the <i>RM</i> bit is reset to 0. This bit is automatically de-asserted back to 0, when the reset is completed. This bit is reserved if on-chip memory is not implemented. | R/W1 | 0 | | | | | | | | | | |
| BF | 14 | Buffer Full indicator that the TCB uses to communicate to external software in the situation that the on-chip trace memory is being deployed in the trace-from and trace-to mode. (See Section 11.13 “TCB On-Chip Trace Memory”) This bit is cleared when writing 1 to the <i>TR</i> bit. This bit is reserved if on-chip memory is not implemented. | R | 0 | | | | | | | | | | |
| TM | 13:12 | Trace Mode. This field determines how the trace memory is filled when using the simple-break control in the PDtrace interface to start or stop trace. <table border="1"><thead><tr><th>TM</th><th>Trace Mode</th></tr></thead><tbody><tr><td>00</td><td>Trace-To</td></tr><tr><td>01</td><td>Trace-From</td></tr><tr><td>10</td><td>Reserved</td></tr><tr><td>11</td><td>Reserved</td></tr></tbody></table> In Trace-To mode, the on-chip trace memory is filled, continuously wrapping around and overwriting older Trace Words, as long as there is trace data coming from the core. In Trace-From mode, the on-chip trace memory is filled from the point that <i>PDO_lamTracing</i> is asserted, and until the on-chip trace memory is full. In both cases, de-asserting the EN bit in this register will also stop fill to the trace memory. If a <i>TCBTRIGx</i> trigger control register is used to start/stop tracing, then this field should be set to Trace-To mode. This bit is reserved if on-chip memory is not implemented. | TM | Trace Mode | 00 | Trace-To | 01 | Trace-From | 10 | Reserved | 11 | Reserved | R/W | 0 |
| TM | Trace Mode | | | | | | | | | | | | | |
| 00 | Trace-To | | | | | | | | | | | | | |
| 01 | Trace-From | | | | | | | | | | | | | |
| 10 | Reserved | | | | | | | | | | | | | |
| 11 | Reserved | | | | | | | | | | | | | |
| TLSIF | 11 | When set, this indicates to the TCB that information about Load and Store data cache miss, instruction cache miss, and function call are to be taken from the PDtrace interface and trace them out in the appropriate trace formats as the three optional bits LSm, Im, and Fcr. | R/W | 0 | | | | | | | | | | |

Table 11.32 TCBCONTROLB Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----------------------|------|---|----------------------|-------------|--|--|--|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|--|---|---|---|---|-----|---|
| Name | Bits | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| CR | 10:8 | <p>Off-chip Clock Ratio. Writing this field, sets the ratio of the core clock to the off-chip trace memory interface clock. The clock-ratio encoding is shown in Table 11.33.</p> <p>Remark: As the Probe interface works in double data rate (DDR) mode, a 1:2 ratio indicates one data packet sent per core clock rising edge.</p> <p>This bit is reserved if off-chip trace option is not implemented.</p> | R/W | 100 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cal | 7 | <p>Calibrate off-chip trace interface.</p> <p>If set to one, the off-chip trace pins will produce the following pattern in consecutive trace clock cycles. If more than 4 data pins exist, the pattern is replicated for each set of 4 pins. The pattern repeats from top to bottom until the Cal bit is de-asserted.</p> <table border="1" data-bbox="654 688 894 1377"> <thead> <tr> <th colspan="5">Calibrations pattern</th></tr> <tr> <th></th><th>3</th><th>2</th><th>1</th><th>0</th></tr> </thead> <tbody> <tr><td></td><td>0</td><td>0</td><td>0</td><td>0</td></tr> <tr><td></td><td>1</td><td>1</td><td>1</td><td>1</td></tr> <tr><td></td><td>0</td><td>0</td><td>0</td><td>0</td></tr> <tr><td></td><td>0</td><td>1</td><td>0</td><td>1</td></tr> <tr><td></td><td>1</td><td>0</td><td>1</td><td>0</td></tr> <tr><td></td><td>1</td><td>0</td><td>0</td><td>0</td></tr> <tr><td></td><td>0</td><td>1</td><td>0</td><td>0</td></tr> <tr><td></td><td>0</td><td>0</td><td>1</td><td>0</td></tr> <tr><td></td><td>0</td><td>0</td><td>0</td><td>1</td></tr> <tr><td></td><td>1</td><td>1</td><td>1</td><td>0</td></tr> <tr><td></td><td>1</td><td>1</td><td>0</td><td>1</td></tr> <tr><td></td><td>1</td><td>0</td><td>1</td><td>1</td></tr> <tr><td></td><td>0</td><td>1</td><td>1</td><td>1</td></tr> </tbody> </table> <p style="writing-mode: vertical-rl; transform: rotate(180deg);">This pattern is replicated for every 4 bits of TR_DATA pins.</p> <p>Note: The clock source of the TCB and PIB must be running.</p> <p>This bit is reserved if off-chip trace option is not implemented.</p> | Calibrations pattern | | | | | | 3 | 2 | 1 | 0 | | 0 | 0 | 0 | 0 | | 1 | 1 | 1 | 1 | | 0 | 0 | 0 | 0 | | 0 | 1 | 0 | 1 | | 1 | 0 | 1 | 0 | | 1 | 0 | 0 | 0 | | 0 | 1 | 0 | 0 | | 0 | 0 | 1 | 0 | | 0 | 0 | 0 | 1 | | 1 | 1 | 1 | 0 | | 1 | 1 | 0 | 1 | | 1 | 0 | 1 | 1 | | 0 | 1 | 1 | 1 | R/W | 0 |
| Calibrations pattern | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 3 | 2 | 1 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 1 | 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 0 | 1 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 1 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 0 | 1 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 0 | 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 1 | 1 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 1 | 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 | 0 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TWSrcVal | 6:3 | These bits are used to indicate the value of the TW source field that will be traced if TWSrcWidth indicates a source bit field width of 2 or 4 bits. Note that if the field is 2 bits, then only bits 4:3 of this field will be used in the TW. | R | Preset | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| CA | 2 | <p>Cycle accurate trace.</p> <p>When set to 1, the trace will include stall information.</p> <p>When set to 0, the trace will exclude stall information, and remove bit zero from all transmitted TF's.</p> <p>The stall information included/excluded is:</p> <ul style="list-style-type: none"> TF6 formats with TCBcode 0001 and 0101. All TF1 formats. | R/W | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Table 11.32 TCBCONTROLB Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Name | Bits | | | |
| OfC | 1 | If set to 1, trace is sent to off-chip memory using <i>TR_DATA</i> pins. If set to 0, trace info is sent to on-chip memory. This bit is read only if a single memory option exists (either off-chip or on-chip only). | R/W | Preset |
| EN | 0 | Enable trace. This is the master enable for trace to be generated from the TCB. This bit can be set or cleared, either by writing this register or from a start/stop/about trigger. When set to 1, trace information is sampled on the <i>PDO_*</i> pins. Trace Words are generated and sent to either on-chip memory or to the Trace Probe. The target of the trace is selected by the OfC bit. When set to 0, trace information on the <i>PDO_*</i> pins is ignored. A potential TF6-stop (from a stop trigger) is generated as the last information, the TCB pipe-line is flushed, and trace output is stopped. | R/W | 0 |

Table 11.33 Clock Ratio encoding of the CR field

| CR/CRMin/CRMax | Clock Ratio |
|----------------|---|
| 000 | 8:1 (Trace clock is eight times that of core clock) |
| 001 | 4:1 (Trace clock is four times that of core clock) |
| 010 | 2:1 (Trace clock is double that of core clock) |
| 011 | 1:1 (Trace clock is same as core clock) |
| 100 | 1:2 (Trace clock is one half of core clock) |
| 101 | 1:4 (Trace clock is one fourth of core clock) |
| 110 | 1:6 (Trace clock is one sixth of core clock) |
| 111 | 1:8 (Trace clock is one eighth of core clock) |

11.9.3 TCBDATA Register

The *TCBDATA* register (0x12) is used to access the registers defined by the *TCBCONTROLB_{REG}* field; see [Table 11.30](#). Regardless of which register or data entry is accessed through *TCBDATA*, the register is only written if the *TCBCONTROLB_{WR}* bit is set. For read-only registers, *TCBCONTROLB_{WR}* is a don't care.

The format of the *TCBDATA* register is shown below, and the field is described in [Table 11.34](#). The width of *TCBDATA* is 64 bits when on-chip trace words (TWs) are accessed (*TCBTW* access).

Figure 11.26 TCBDATA Register Format

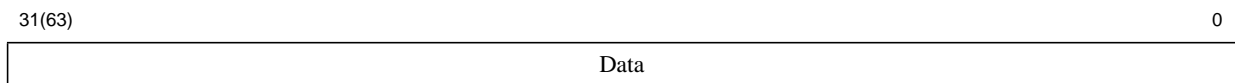


Table 11.34 TCBDATA Register Field Descriptions

| Fields | | Description | Read/Write | Reset State |
|--------|--------------|--|---|-------------|
| Names | Bits | | | |
| Data | 31:0 63:0 | Register fields or data as defined by the <i>TCBCONTROLB_{REG}</i> field | Only writable if <i>TCBCONTROLB_{WR}</i> is set | 0 |

11.9.4 TCBCONTROLC Register

The trace output from the processor on the PDtrace interface can be controlled by the trace input signals to the processor from the TCB. The TCB uses a control register, *TCBCONTROLC*, whose values are used to change the signal values on the PDtrace input interface. External software (i.e., debugger) can therefore manipulate the trace output by writing to this register.

The *TCBCONTROLC* register is written by the EJTAG TAP controller instruction, TCBCONTROLC (0x13).

The format of the *TCBCONTROLC* register is shown below, and the fields are described in Table 11.35.

Figure 11.27 TCBCONTROLC Register Format

| | | | | | | | | | | | | | | | | |
|-----|------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 31 | 28 | 27 | 23 | 22 | 21 | 15 | 14 | 13 | 12 | 9 | 8 | 5 | 4 | 2 | 1 | 0 |
| Res | Mode | | Res | Res | Res | Res | Res | Res | Res | Res | Res | Res | Res | Res | Res | Res |

Table 11.35 TCBCONTROLC Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | | | |
|-----------|---------------------|---|--------------|---------------------|---|----|---|--------------|---|---------------|---|-----------|---|------------|-----|---|
| Name | Bits | | | | | | | | | | | | | | | |
| Res | 31:28 | Reserved for future use. Must be written as zero; returns zero on read. | 0 | 0 | | | | | | | | | | | | |
| Mode | 27:23 | <div>When tracing is turned on, this signal specifies what information is to be traced by the core. It uses 5 bits, where each bit turns on a tracing of a specific tracing mode.</div> <table><tr><th>Bit # Set</th><th>Trace The Following</th></tr><tr><td>0</td><td>PC</td></tr><tr><td>1</td><td>Load address</td></tr><tr><td>2</td><td>Store address</td></tr><tr><td>3</td><td>Load data</td></tr><tr><td>4</td><td>Store data</td></tr></table> <div>The table shows what trace value is turned on when that bit value is a 1. If the corresponding bit is 0, then the Trace Value shown in column two is not traced by the processor. On the 24K core PC tracing is always enabled, regardless of the value on bit 23. This field defines the value on the <i>PDI_TraceMode</i> signal.</div> | Bit # Set | Trace The Following | 0 | PC | 1 | Load address | 2 | Store address | 3 | Load data | 4 | Store data | R/W | 0 |
| Bit # Set | Trace The Following | | | | | | | | | | | | | | | |
| 0 | PC | | | | | | | | | | | | | | | |
| 1 | Load address | | | | | | | | | | | | | | | |
| 2 | Store address | | | | | | | | | | | | | | | |
| 3 | Load data | | | | | | | | | | | | | | | |
| 4 | Store data | | | | | | | | | | | | | | | |
| Res | 22:0 | Reserved for future use. Must be written as zero; returns zero on read. | 0 | 0 | | | | | | | | | | | | |

11.9.5 TCBCONFIG Register (Reg 0)

The *TCBCONFIG* register holds information about the hardware configuration of the TCB. The format of the *TCBCONFIG* register is shown below, and the field is described in [Table 11.36](#).

Figure 11.28 TCBCONFIG Register Format

| | | | | | | | | | | | | | | | | | | |
|-----|----|------|----|-------|-------|----|-----|-----|-----|-----|----|---|---|---|---|---|---|---|
| 31 | 30 | 25 | 24 | 21 | 20 | 17 | 16 | 14 | 13 | 11 | 10 | 9 | 8 | 6 | 5 | 4 | 3 | 0 |
| CF1 | 0 | TRIG | SZ | CRMax | CRMin | PW | PiN | OnT | OfT | REV | | | | | | | | |

Table 11.36 TCBCONFIG Register Field Descriptions

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|--------|---------------------------------------|---|--------------|---------------------------------------|----|--------|----|--------|----|---------|----|----------|---|--------|
| Name | Bits | | | | | | | | | | | | | |
| CF1 | 31 | This bit is set if a <i>TCBCONFIG1</i> register exists. In this revision, <i>TCBCONFIG1</i> does not exist and this bit always reads zero. | R | 0 | | | | | | | | | | |
| 0 | 30:25 | Reserved. Must be written as zero; returns zero on read. | R | 0 | | | | | | | | | | |
| TRIG | 24:21 | Number of triggers implemented. This also indicates the number of <i>TCBTRIGx</i> registers that exist. | R | Preset Legal values are 0 - 8 | | | | | | | | | | |
| SZ | 20:17 | On-chip trace memory size. This field holds the encoded size of the on-chip trace memory. The size in bytes is given by 2 ^(SZ+8) , implying that the minimum size is 256 bytes and the largest is 8Mb. This bit is reserved if on-chip memory is not implemented. | R | Preset | | | | | | | | | | |
| CRMax | 16:14 | Off-chip Maximum Clock Ratio. This field indicates the maximum ratio of the core clock to the off-chip trace memory interface clock. The clock-ratio encoding is shown in Table 11.33 . This bit is reserved if off-chip trace option is not implemented. | R | Preset | | | | | | | | | | |
| CRMin | 13:11 | Off-chip Minimum Clock Ratio. This field indicates the minimum ratio of the core clock to the off-chip trace memory interface clock. The clock-ratio encoding is shown in Table 11.33 . This bit is reserved if off-chip trace option is not implemented. | R | Preset | | | | | | | | | | |
| PW | 10:9 | Probe Width: Number of bits available on the off-chip trace interface <i>TR_DATA</i> pins. The number of <i>TR_DATA</i> pins is encoded, as shown in the table. <table border="1"><thead><tr><th>PW</th><th>Number of bits used on <i>TR_DATA</i></th></tr></thead><tbody><tr><td>00</td><td>4 bits</td></tr><tr><td>01</td><td>8 bits</td></tr><tr><td>10</td><td>16 bits</td></tr><tr><td>11</td><td>reserved</td></tr></tbody></table> This field is preset based on input signals to the TCB and the actual capability of the TCB. This bit is reserved if off-chip trace option is not implemented. | PW | Number of bits used on <i>TR_DATA</i> | 00 | 4 bits | 01 | 8 bits | 10 | 16 bits | 11 | reserved | R | Preset |
| PW | Number of bits used on <i>TR_DATA</i> | | | | | | | | | | | | | |
| 00 | 4 bits | | | | | | | | | | | | | |
| 01 | 8 bits | | | | | | | | | | | | | |
| 10 | 16 bits | | | | | | | | | | | | | |
| 11 | reserved | | | | | | | | | | | | | |
| PiN | 8:6 | Pipe number. Indicates the number of execution pipelines. | R | 0 | | | | | | | | | | |

Table 11.36 TCBCONFIG Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|--|--------------|-------------|
| Name | Bits | | | |
| OnT | 5 | When set, this bit indicates that on-chip trace memory is present. This bit is preset based on the selected option when the TCB is implemented. | R | Preset |
| OfT | 4 | When set, this bit indicates that off-chip trace interface is present. This bit is preset based on the selected option when the TCB is implemented, and on the existence of a PIB module (<i>TC_PibPresent</i> asserted). | R | Preset |
| REV | 3:0 | Revision of TCB. An implementation that conforms to PDtrace version 4.x must have a value of 1 for this field. | R | 1 |

11.9.6 TCBTW Register (Reg 4)

The *TCBTW* register is used to read Trace Words from the on-chip trace memory. The TW read is the one pointed to by the *TCBRDP* register. A side effect of reading the *TCBTW* register is that the *TCBRDP* register increments to the next TW in the on-chip trace memory. If *TCBRDP* is at the max size of the on-chip trace memory, the increment wraps back to address zero.

This register is reserved if on-chip trace memory is not implemented.

The format of the *TCBTW* register is shown below, and the field is described in [Table 11.37](#).

Figure 11.29 TCBTW Register Format

| | |
|------|---|
| 63 | 0 |
| Data | |

Table 11.37 TCBTW Register Field Descriptions

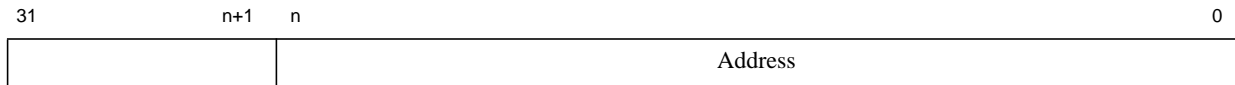
| Fields | | Description | Read / Write | Reset State |
|--------|------|-------------|--------------|-------------|
| Names | Bits | | | |
| Data | 63:0 | Trace Word | R/W | 0 |

11.9.7 TCBRDP Register (Reg 5)

The *TCBRDP* register is the address pointer to on-chip trace memory. It points to the TW read when reading the *TCBTW* register. When writing the *TCBCTRLB_{RM}* bit to 1, this pointer is reset to the current value of *TCBSTP*.

This register is reserved if on-chip trace memory is not implemented.

The format of the *TCBRDP* register is shown below, and the field is described in [Table 11.38](#). The value of n depends on the size of the on-chip trace memory. As the address points to a 64-bit TW, lower three bits are always zero.

Figure 11.30 TCBRDP Register Format**Table 11.38 TCBRDP Register Field Descriptions**

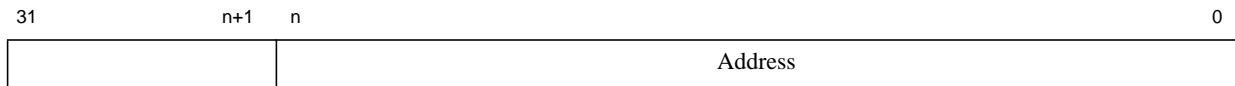
| Fields | | Description | Read / Write | Reset State |
|---------|----------|--|--------------|-------------|
| Names | Bits | | | |
| Data | 31:(n+1) | Reserved. Must be written zero, reads back zero. | 0 | 0 |
| Address | n:0 | Byte address of on-chip trace memory word. | R/W | 0 |

11.9.8 TCBWRP Register (Reg 6)

The *TCBWRP* register is the address pointer to on-chip trace memory. It points to the location where the next new TW for on-chip trace will be written.

This register is reserved if on-chip trace memory is not implemented.

The format of the *TCBWRP* register is shown below, and the fields are described in Table 11.39. The value of *n* depends on the size of the on-chip trace memory. As the address points to a 64-bit TW, the lower three bits are always zero.

Figure 11.31 TCBWRP Register Format**Table 11.39 *TCBWRP* Register Field Descriptions**

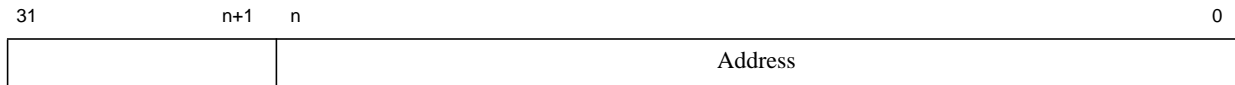
| Fields | | Description | Read / Write | Reset State |
|---------|----------|--|--------------|-------------|
| Names | Bits | | | |
| Data | 31:(n+1) | Reserved. Must be written zero, reads back zero. | 0 | 0 |
| Address | n:0 | Byte address of on-chip trace memory word. | R/W | 0 |

11.9.9 TCBSTP Register (Reg 7)

The *TCBSTP* register is the start pointer register. This register points to the on-chip trace memory address at which the oldest TW is located. This pointer is reset to zero when the *TCBCONTROLB_{TR}* bit is written to 1. If a continuous trace to on-chip memory wraps around the on-chip memory, *TCBSTP* will have the same value as *TCBWRP*.

This register is reserved if on-chip trace memory is not implemented.

The format of the *TCBSTP* register is shown below, and the fields are described in Table 11.40. The value of *n* depends on the size of the on-chip trace memory. As the address points to a 64-bit TW, lower three bits are always zero.

Figure 11.32 TCBSTP Register Format**Table 11.40 TCBSTP Register Field Descriptions**

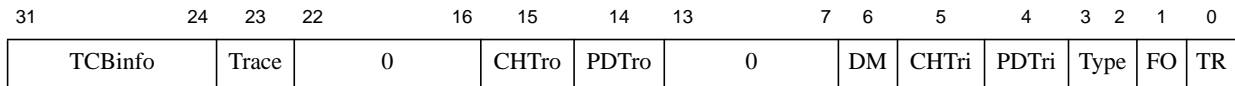
| Fields | | Description | Read / Write | Reset State |
|---------|----------|--|--------------|-------------|
| Names | Bits | | | |
| Data | 31:(n+1) | Reserved. Must be written zero, reads back zero. | 0 | 0 |
| Address | n:0 | Byte address of on-chip trace memory word. | R/W | 0 |

11.9.10 TCBTRIGx Register (Reg 16-23)

Up to eight Trigger Control registers are possible. Each register is named *TCBTRIGx*, where *x* is a single digit number from 0 to 7 (*TCBTRIG0* is Reg 16). The actual number of trigger registers implemented is defined in the *TCBCONFIG_{TRIG}* field. An unimplemented register will read all zeros and writes are ignored.

Each Trigger Control register controls when an associated trigger is fired, and the action to be taken when the trigger occurs. Please also read [Section 11.11 “TCB Trigger Logic”](#), for detailed description of trigger logic issues.

The format of the *TCBTRIGx* register is shown below, and the fields are described in [Table 11.41](#).

Figure 11.33 TCBTRIGx Register Format**Table 11.41 TCBTRIGx Register Field Descriptions**

| Fields | | Description | Read / Write | Reset State |
|---------|-------|--|--------------|-------------|
| Names | Bits | | | |
| TCBInfo | 31:24 | This field is to be used in a possible TF6 trace format when this trigger fires. | R/W | 0 |
| Trace | 23 | When set, generate TF6 trace information when this trigger fires. Use <i>TCBInfo</i> field for the TCBInfo of TF6 and use <i>Type</i> field for the two MSB of the TCbtype of TF6. The two LSB of <i>TCBtype</i> are 00. The write value of this bit always controls the behavior of this trigger. When this trigger fires, the read value will change to indicate if the TF6 format was ever suppressed by a simultaneous trigger. If so, the read value will be 0. If the write value was 0, the read value is always 0. This special read value is valid until the <i>TCBTRIGx</i> register is written. | R/W | 0 |
| 0 | 22:16 | Reserved. Must be written as zero; returns zero on read. | R | 0 |
| CHTro | 15 | When set, generate a single cycle strobe on <i>TC_ChipTrigOut</i> when this trigger fires. | R/W | 0 |
| PDTro | 14 | When set, generate a single cycle strobe on <i>TC_ProbeTrigOut</i> when this trigger fires. | R/W | 0 |

Table 11.41 TCBTRIGx Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State |
|--------|------|---|--------------|-------------|
| Names | Bits | | | |
| 0 | 13:7 | Reserved. Must be written as zero; returns zero on read. | R | 0 |
| DM | 6 | When set, this Trigger will fire when a rising edge on the Debug mode indication from the core is detected. The write value of this bit always controls the behavior of this trigger. When this trigger fires, the read value will change to indicate if this source was ever the cause of a trigger action (even if the action was suppressed). If so the read value will be 1. If the write value was 0 the read value is always 0. This special read value is valid until the <i>TCBTRIGx</i> register is written. | R/W | 0 |
| CHTri | 5 | When set, this Trigger will fire when a rising edge on <i>TC_ChipTrigIn</i> is detected. The write value of this bit always controls the behavior of this trigger. When this trigger fires, the read value will change to indicate if this source was ever the cause of a trigger action (even if the action was suppressed). If so the read value will be 1. If the write value was 0 the read value is always 0. This special read value is valid until the <i>TCBTRIGx</i> register is written. | R/W | 0 |
| PDTri | 4 | When set, this Trigger will fire when a rising edge on <i>TC_ProbeTrigIn</i> is detected. The write value of this bit always controls the behavior of this trigger. When this trigger fires, the read value will change to indicate if this source was ever the cause of a trigger action (even if the action was suppressed). If so the read value will be 1. If the write value was 0 the read value is always 0. This special read value is valid until the <i>TCBTRIGx</i> register is written. | R/W | 0 |

Table 11.41 TCBTRIGx Register Field Descriptions (Continued)

| Fields | | Description | Read / Write | Reset State | | | | | | | | | | |
|--------|--|---|--------------|----------------|----|---|----|---|----|--|----|--|-----|---|
| Names | Bits | | | | | | | | | | | | | |
| Type | 3:2 | <p>Trigger Type: The Type indicates the action to take when this trigger fires. The table below show the Type values and the Trigger action.</p> <table><tr><th>Type</th><th>Trigger action</th></tr><tr><td>00</td><td>Trigger Start: Trigger start-point of trace.</td></tr><tr><td>01</td><td>Trigger End: Trigger end-point of trace.</td></tr><tr><td>10</td><td>Trigger About: Trigger center-point of trace.</td></tr><tr><td>11</td><td>Trigger Info: No action trigger, only for trace info.</td></tr></table> <p>The actual action is to set or clear the <i>TCBCONTROLB_{EN}</i> bit. A Start trigger will set <i>TCBCONTROLB_{EN}</i>, a End trigger will clear <i>TCBCONTROLB_{EN}</i>. The About trigger will clear <i>TCBCONTROLB_{EN}</i> half way through the trace memory, from the trigger. The size determined by the <i>TCBCONFIG_{SZ}</i> field for on-chip memory. Or from the <i>TCBCONTROLA_{SyP}</i> field for off-chip trace.</p> <p>If Trace is set, then a TF6 format is added to the trace words. For Start and Info triggers this is done before any other TF's in that same cycle. For End and About triggers, the TF6 format is added after any other TF's in that same cycle.</p> <p>If the <i>TCBCONTROLB_{TM}</i> field is implemented it must be set to Trace-To mode (00), for the <i>Type</i> field to control on-chip trace fill. The write value of this bit always controls the behavior of this trigger.</p> <p>When this trigger fires, the read value will change to indicate if the trigger action was ever suppressed. If so the read value will be 11. If the write value was 11 the read value is always 11. This special read value is valid until the <i>TCBTRIGx</i> register is written.</p> | Type | Trigger action | 00 | Trigger Start: Trigger start-point of trace. | 01 | Trigger End: Trigger end-point of trace. | 10 | Trigger About: Trigger center-point of trace. | 11 | Trigger Info: No action trigger, only for trace info. | R/W | 0 |
| Type | Trigger action | | | | | | | | | | | | | |
| 00 | Trigger Start: Trigger start-point of trace. | | | | | | | | | | | | | |
| 01 | Trigger End: Trigger end-point of trace. | | | | | | | | | | | | | |
| 10 | Trigger About: Trigger center-point of trace. | | | | | | | | | | | | | |
| 11 | Trigger Info: No action trigger, only for trace info. | | | | | | | | | | | | | |
| FO | 1 | Fire Once. When set, this trigger will not re-fire until the <i>TR</i> bit is de-asserted. When de-asserted this trigger will fire each time one of the trigger sources indicates trigger. | R/W | 0 | | | | | | | | | | |
| TR | 0 | <p>Trigger happened. When set, this trigger fired since the <i>TR</i> bit was last written 0.</p> <p>This bit is used to inspect whether the trigger fired since this bit was last written zero.</p> <p>When set, all the trigger source bits (bit 4 to 13) will change their read value to indicate if the particular bit was the source to fire this trigger. Only enabled trigger sources can set the read value, but more than one is possible.</p> <p>Also when set the <i>Type</i> field and the <i>Trace</i> field will have read values which indicate if the trigger action was ever suppressed by a higher priority trigger.</p> | R/W0 | 0 | | | | | | | | | | |

11.9.11 Register Reset State

Reset state for all register fields is entered when either of the following occur:

1. TAP controller enters/is in Test-Logic-Reset state.

2. *EJ_TRST_N* input is asserted low.

11.10 Enabling MIPS Trace

As there are several ways to enable tracing, it can be quite confusing to figure out how to turn tracing on and off. This section should help clarify the enabling of trace.

11.10.1 Trace Trigger from EJTAG Hardware Instruction/Data Breakpoints

If hardware instruction/data simple breakpoints are implemented in the 24K core, then these breakpoint can be used as triggers to start/stop trace. When used for this, the breakpoints need not also generate a debug exception, but are capable of only generating an internal trigger to the trace logic. This is done by only setting the TE bit and not the BE bit in the Breakpoint Control register. Please see [Section 11.2.8.5 “Instruction Breakpoint Control n \(IBCn\) Register”](#) and [Section 11.2.9.5 “Data Breakpoint Control n \(DBCn\) Register”](#), for details on breakpoint control.

In connection with the breakpoints, the Trace BreakPoint Control (*TraceBPC*) register is used to define the trace action when a trigger happens. When a breakpoint is enabled as a trigger (TE = 1), it can be selected to be either a start or a stop trigger to the trace logic. Please see [Section 6.2.32 “TraceIBPC Register \(CP0 Register 23, Select 4\)”](#) for detail in how to define a start/stop trigger.

11.10.2 Turning On PDtrace™ Trace

Trace enabling and disabling from software is similar to the hardware method, with the exception that the bits in the control register are used instead of the input enable signals from the TCB. The *TraceControl_{TS}* bit controls whether hardware (via the TCB), or software (via the *TraceControl* register) controls tracing functionality.

Trace is turned on when the following expression evaluates true:

```
(
  (
    (TraceControlTS and TraceControlOn) or
    ((not TraceControlTS) and TCBCONTROLAOn)
  )
  and
  (MatchEnable or TriggerEnable)
)
```

where,

```
MatchEnable ←
(
  TraceControlTS
  and
  (
    TraceControlG or
    (((TraceControlASID xor EntryHiASID) and (not TraceControlASID_M)) = 0)
  )
  and
  (
    (TraceControlU and UserMode) or
    (TraceControlS and SupervisorMode) or
    (TraceControlK and KernelMode) or
    (TraceControlE and ExceptionMode) or
    (TraceControlD and DebugMode)
  )
)
```

```

    )
  )
  or
  (
    (not TraceControlTS)
    and
    (TCBCONTROLAG or (TCBCONTROLAASID = EntryHiASID))
    and
    (
      (TCBCONTROLAU and UserMode)      or
      (TCBCONTROLAS and SupervisorMode) or
      (TCBCONTROLAK and KernelMode)    or
      (TCBCONTROLAE and ExceptionMode) or
      (TCBCONTROLADM and DebugMode)
    )
  )
)

```

and where,

```

TriggerEnable ←
(
  DBCiTE      and
  DBSBS[i]    and
  TraceBPCDE  and
  (TraceBPCDBPOn[i] = 1)
)
or
(
  IBCiTE      and
  IBSBS[i]    and
  TraceBPCIE  and
  (TraceBPCIBPOn[i] = 1)
)

```

As seen in the expression above, trace can be turned on only if the master switch *TraceControl_{On}* or *TCBCONTROLA_{On}* is first asserted.

Once this is asserted, there are two ways to turn on tracing. The first way, the *MatchEnable* expression, uses the input enable signals from the TCB or the bits in the *TraceControl* register. This tracing is done over general program areas. For example, all of the user-level code for a particular process (if ASID is specified), and so on.

The second way to turn on tracing, the *TriggerEnable* expression, is from the processor side using the EJTAG hardware breakpoint triggers. If EJTAG is implemented, and hardware breakpoints can be set, then using this method enables finer grain tracing control. It is possible to send a trigger signal that turns on tracing at a particular instruction. For example, it would be possible to trace a single procedure in a program by triggering on trace at the first instruction, and triggering off trace at the last instruction.

The easiest way to unconditionally turn on trace is to assert either hardware or software tracing and the corresponding trace on signal with other enables. For example, with *TraceControl_{TS}*=0, i.e., hardware controlled tracing, assert *TCBCONTROLA_{On}*, *TCBCONTROLA_G*, and all the other signals in the second part of expression *MatchEnable*. To only trace when a particular process with a known ASID is executing, assert *TCBCONTROLA_{On}*, the correct *TCBCONTROLA_{ASID}* value, and all of *TCBCONTROLA_U*, *TCBCONTROLA_K*, *TCBCONTROLA_E*, and *TCBCONTROLA_{DM}*. (If it is known that the particular process is a user-level process, then it would be sufficient to only assert *TCBCONTROLA_U* for example). When using the EJTAG hardware triggers to turn trace on and off, it is best if *TCBCONTROLA_{On}* is asserted and all the other processor mode selection bits in *TCBCONTROLA* are turned

off. This would be the least confusing way to control tracing with the trigger signals. Tracing can be controlled via software with the *TraceControl* register in a similar manner.

11.10.3 Turning Off PDtrace™ Trace

Trace is turned off when the following expression evaluates true:

```
(
    (TraceControlTS and (not TraceControlOn)) or
    ((not TraceControlTS) and (not TCBCONTROLAOn))
)
or
(
    (not MatchEnable)      and
    (not TriggerEnable)    and
    TriggerDisable
)
```

where,

```
TriggerDisable ←
(
    DBCiTE      and
    DBSBS[i]    and
    TraceBPCDE  and
    (TraceBPCDBPOn[i] = 0)
)
or
(
    IBCiTE      and
    IBSBS[i]    and
    TraceBPCIE  and
    (TraceBPCIBPOn[i] = 0)
)
```

Tracing can be unconditionally turned off by de-asserting the *TraceControl_{On}* bit or the *TCBCONTROLA_{On}* signal. When either of these are asserted, tracing can be turned off if all of the enables are de-asserted, irrespective of the *TraceControl_G* bit (*TCBCONTROLA_G*) and *TraceControl_{ASID}* (*TCBCONTROLA_{ASID}*) values. EJTAG hardware breakpoints can be used to trigger trace off as well. Note that if simultaneous triggers are generated, and even one of them turns on tracing, then even if all of the others attempt to trigger trace off, then tracing will still be turned on. This condition is reflected in presence of the “(not TriggerEnable)” term in the expression above.

11.10.4 TCB Trace Enabling

The TCB must be enabled in order to produce a trace on the probe or to on-chip memory, when trace information is sent on the PDtrace™ interface. The main switch for this is the *TCBCONTROLB_{EN}* bit. When set, the TCB will send trace information to either on-chip trace memory or to the Trace Probe, controlled by the setting of the *TCBCONTROLB_{OfC}* bit.

The TCB can optionally include trigger logic, which can control the *TCBCONTROLB_{EN}* bit. Please see [Section 11.11 “TCB Trigger Logic”](#) for details.

11.10.5 Tracing a Reset Exception

Tracing a reset exception is possible. However, the *TraceControl*_{TS} bit is reset to 0 at core reset, so all the trace control must be from the TCB (using *TCBCONTROLA* and *TCBCONTROLB*). The PDtrace fifo and the entire TCB are reset based on an EJTAG reset. It is thus possible to set up the trace modes, etc., using the TAP controller, and then reset the processor core.

11.11 TCB Trigger Logic

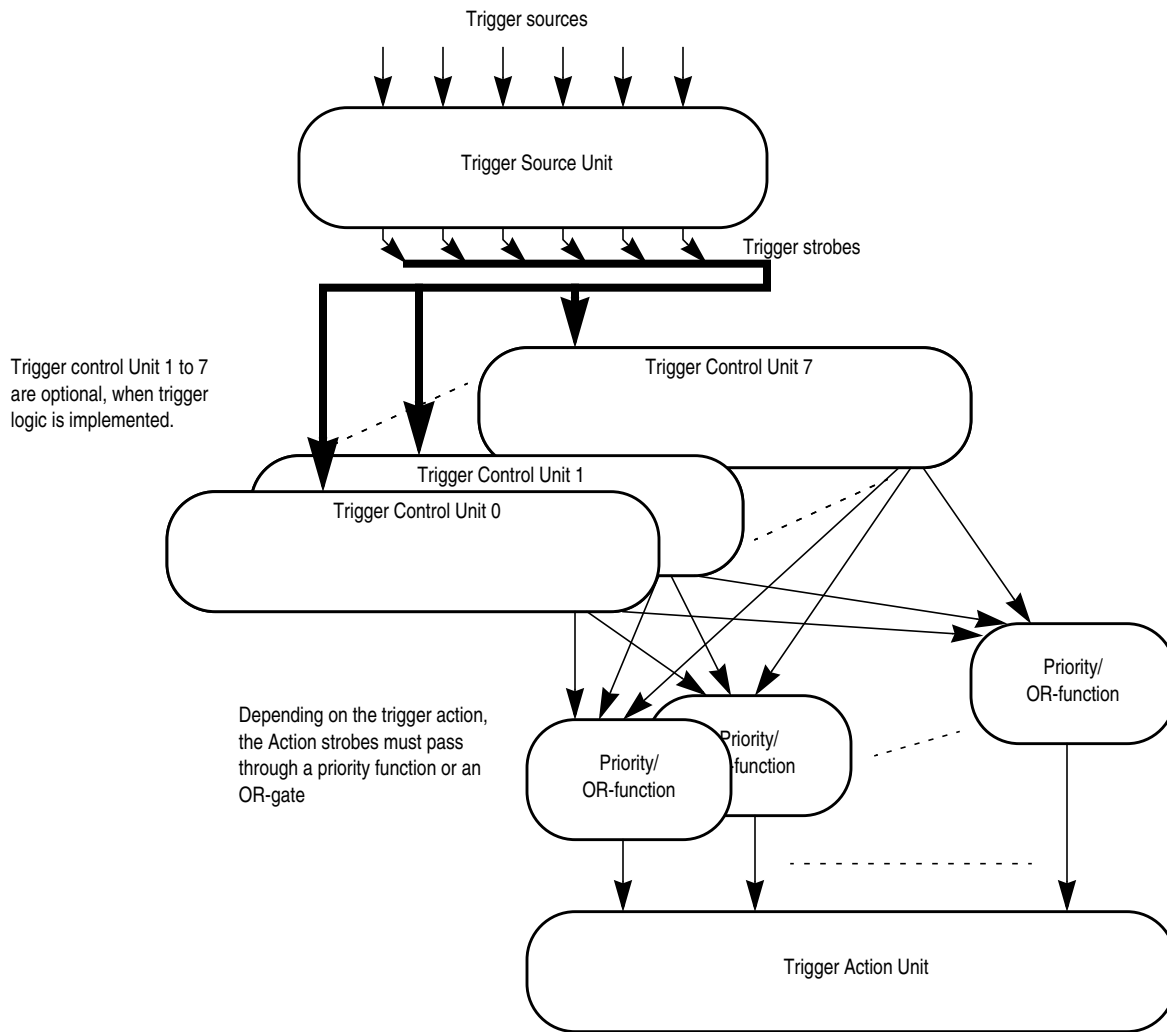
The TCB is optionally implemented with trigger unit. If this is the case, then the *TCBCONFIG*_{TRIG} field is non-zero. This section will explain some of the issues around triggers in the TCB.

11.11.1 Trigger Units Overview

TCB trigger logic features three main parts:

1. A common Trigger Source detection unit.
2. 1 to 8 separate Trigger Control units.
3. A common Trigger Action unit.

[Figure 11.34](#) show the functional overview of the trigger flow in the TCB.

Figure 11.34 TCB Trigger Processing Overview

11.11.2 Trigger Source Unit

The TCB has three trigger sources:

1. Chip-level trigger input (*TC_ChipTrigIn*).
2. Probe trigger input (*TR_TRIGIN*).
3. Debug Mode (DM) entry indication from the processor core.

The input triggers are all rising-edge triggers, and the Trigger Source Units convert the edge into a single cycle strobe to the Trigger Control Units.

11.11.3 Trigger Control Units

Up to eight Trigger Control Units are possible. Each of them has its own Trigger Control Register (*TCBTRIG_x*, $x=\{0..7\}$). Each of these registers controls the trigger fire mechanism for the unit. Each unit has all of the Trigger Sources as possible trigger event and they can fire one or more of the Trigger Actions. This is all defined in the Trigger Control register *TCBTRIG_x* (see [Section 11.9.10 “TCBTRIG_x Register \(Reg 16-23\)”](#)).

11.11.4 Trigger Action Unit

The TCB has four possible trigger actions:

1. Chip-level trigger output (*TC_ChipTrigOut*).
2. Probe trigger output (*TR_TRIGOUT*).
3. Trace information. Put a programmable byte into the trace stream from the TCB.
4. Start, End or About (delayed end) control of the *TCBCONTROLB_{EN}* bit.

The basic function of the trigger actions is explained in [Section 11.9.10 “TCBTRIG_x Register \(Reg 16-23\)”](#). Please also read the next [Section 11.11.5 “Simultaneous Triggers”](#).

11.11.5 Simultaneous Triggers

Two or more triggers can fire simultaneously. The resulting behavior depends on trigger action set for each of them, and whether they should produce a TF6 trace information output or not. There are two groups of trigger actions: Prioritized and OR'ed.

11.11.5.1 Prioritized Trigger Actions

For prioritized simultaneous trigger actions, the trigger control unit which has the lowest number takes precedence over the higher numbered units. The x in *TCBTRIG_x* registers defines the number. The oldest trigger takes precedence over everything.

The following trigger actions are prioritized when two or more units fire simultaneously:

- Trigger Start, End and About type triggers (*TCBTRIG_{xType}* field set to 00, 01 or 10), which will assert/de-assert the *TCBCONTROLB_{EN}* bit. The About trigger is delayed and will always change *TCBCONTROLB_{EN}* because it is the oldest trigger when it de-asserts *TCBCONTROLB_{EN}*. An About trigger will not start the countdown if an even older About trigger is using the Trace Word counter.
- Triggers which produce TF6 trace information in the trace flow (Trace bit is set).

Regardless of priority, the *TCBTRIG_{xTR}* bit is set when the trigger fires. This is so even if a trigger action is suppressed by a higher priority trigger action. If the trigger is set to only fire once (the *TCBTRIG_{xFO}* bit is set), then the suppressed trigger action will not happen until after *TCBTRIG_{xTR}* is written 0.

If a Trigger action is suppressed by a higher priority trigger, then the read value, when the *TCBTRIG_{xTR}* bit is set, for the *TCBTRIG_{xTrace}* field will be 0 for suppressed TF6 trace information actions. The read value in the *TCBTRIG_{xType}* field for suppressed Start/End/About triggers will be 11. This indication of a suppressed action is sticky. If any of the

two actions (Trace and Type) are ever suppressed for a multi-fire trigger (the $TCBTRIGx_{FO}$ bit is zero), then the read values in Trace and/or Type are set to indicate any suppressed action.

About Trigger

The About triggers delayed de-assertion of the $TCBCONTROLB_{EN}$ bit is always executed, regardless of priority from another Start trigger at the time of the $TCBCONTROLB_{EN}$ change. This means that if a simultaneous About trigger action on the $TCBCONTROLB_{EN}$ bit (n/2 Trace Words after the trigger) and a Start trigger hit the same cycle, then the About trigger wins, regardless of which trigger number it is. The oldest trigger takes precedence.

However, if an About trigger has started the count down from n/2, but not yet reached zero, then a new About trigger, will NOT be executed. Only one About trigger can have the cycle counter. This second About trigger will store 11 in the $TCBTRIGx_{Type}$ field. But, if the $TCBTRIGx_{Trace}$ bit is set, a TF6 trace information will still go in the trace.

11.11.5.2 OR'ed Trigger Actions

The simple trigger actions CHTro and PDTro from each trigger unit, are effectively OR'ed together to produce the final trigger. One or more expected trigger strobes on i.e. $TC_ChipTrigOut$ can thus disappear. External logic should not rely on counting of strobes, to predict a specific event, unless simultaneous triggers are known not to occur.

11.12 MIPS Trace Cycle-by-Cycle Behavior

A key reason for using trace, and not single stepping to debug a software problem, is often to get a picture of the real-time behavior. However the trace logic itself can, when enabled, affect the exact cycle-by-cycle behavior,

11.12.1 FIFO Logic in PDtrace and TCB Modules

Both the PDtrace module and the TCB module contain a fifo. This might seem like extra overhead, but there are good reasons for this. The vast majority of the information compression happens in the PDtrace module. Any data information, like PC and load/store address values (delta or full), load/store data and processor mode changes, are all sent on the same 32-bit data bus to the TCB on the internal PDtrace™ interface. When an instruction requires more than 32 bits of information to be traced properly, the PDtrace fifo will buffer the information, and send it on subsequent clock cycles.

In the TCB, the on-chip trace memory is defined as a 64-bit wide synchronous memory running at core-clock speed. In this case the fifo is not needed. For off-chip trace through the Trace Probe, the fifo comes into play, because only a limited number of pins (4, 8 or 16) exist. Also the speed of the Trace Probe interface can be different (either faster or slower) from that of the 24K core. So for off-chip tracing, a specific TCB TW fifo is needed.

11.12.2 Handling of FIFO Overflow in the PDtrace Module

Depending on the amount of trace information selected for trace, and the frequency with which the 32-bit data interface is needed, it is possible for the PDtrace fifo overflow from time to time. There are two ways to handle this case:

1. Allow the overflow to happen, and thereby lose some information from the trace data.
2. Prevent the overflow by back-stalling the core, until the fifo has enough empty slots to accept new trace data.

The PDtrace fifo option is controlled by either the $TraceControl_{IO}$ or the $TCBCONTROLA_{IO}$ bit, depending on the setting of $TraceControl_{TS}$ bit.

The first option is free of any cycle-by-cycle change whether trace is turned on or not. This is achieved at the cost of potentially losing trace information. After an overflow, the fifo is completely emptied, and the next instruction is traced as if it was the start of the trace (processor mode and full PC are traced). This guarantees that only the un-traced fifo information is lost.

The second option guarantees that all the trace information is traced to the TCB. In some cases this is then achieved by back-stalling the core pipeline, giving the PDtrace fifo time to empty enough room in the fifo to accept new trace information from a new instruction. This option can obviously change the real-time behavior of the core when tracing is turned on.

If PC trace information is the only thing enabled (in *TraceControl2_{MODE}* or *TCBCONTROL_C_{MODE}*, depending on the setting of *TraceControl_{TS}*), and Trace of all branches is turned off (via *TraceControl_{TB}* or *TCBCONTROL_A_{TB}*, depending on the setting of *TraceControl_{TS}*), then the fifo is unlikely to overflow very often, if at all. This is of course very dependent on the code executed, and the frequency of exception handler jumps, but with this setting there is very little information overhead.

11.12.3 Handling of FIFO Overflow in the TCB

The TCB also holds a fifo, used to buffer the TW's which are sent off-chip through the Trace Probe. The data width of the probe can be either 4, 8 or 16 pins, and the speed of these data pins can be from 16 times the core-clock to 1/4 of the core clock (the trace probe clock always runs at a double data rate multiple to the core-clock). See [Section 11.12.3.1 "Probe Width and Clock-ratio Settings"](#) for a description of probe width and clock-ratio options. The combination between the probe width (4, 8 or 16) and the data speed, allows for data rates through the trace probe from 256 bits per core-clock cycle down to only 1 bit per core-clock cycle. The high extreme is not likely to be supported in any implementation, but the low one might be.

The data rate is an important figure when the likelihood of a TCB fifo overflow is considered. The TCB will at maximum produce one full 64-bit TW per core-clock cycle. This is true for any selection of trace mode in *TraceControl2_{MODE}* or *TCBCONTROL_C_{MODE}*. The PDtrace module will guarantee the limited amount of data. If the TCB data rate cannot be matched by the off-chip probe width and data speed, then the TCB fifo can possibly overflow. Similar to the PDtrace module FIFO, this can be handled in two ways:

1. Allow the overflow to happen, and thereby lose some information from the trace data.
2. Prevent the overflow by asserting a stall-signal back to the core (*PDI_StallSending*). This will in turn stall the core pipeline.

As a practical matter, the amount of data to the TCB can be minimized by only tracing PC information and excluding any cycle accurate information. This is explained in [Section 11.12.2 "Handling of FIFO Overflow in the PDtrace Module"](#) and below in [Section 11.12.4 "Adding Cycle Accurate Information to the Trace"](#). With this setting, a data rate of 8-bits per core-clock cycle is usually sufficient. No guarantees can be given here, however, as heavy interrupt activity can increase the number of unpredictable jumps considerably.

11.12.3.1 Probe Width and Clock-ratio Settings

The actual number of data pins (4, 8 or 16) is defined by the *TCBCONFIG_{PW}* field. Furthermore, the frequency of the Trace Probe can be different from the core-clock frequency. The trace clock (*TR_CLK*) is a double data rate clock. This means that the data pins (*TR_DATA*) change their value on both edges of the trace clock. When the trace clock is running at clock ratio of 1:2 (one half) of core clock, the data output registers are running a core-clock frequency. The clock ratio is set in the *TCBCONTROL_B_{CR}* field. The legal range for the clock ratio is defined in *TCBCONFIG_{CRMax}* and *TCBCONFIG_{CRMin}* (both values inclusive). If *TCBCONTROL_B_{CR}* is set to an unsupported value, the result is UNPREDICABLE. The maximum possible value for *TCBCONFIG_{CRMax}* is 8:1 (*TR_CLK* is running 8 times faster

than core-clock). The minimum possible value for $TCBCONFIG_{CRMin}$ is 1:8 (TR_CLK is running at one eighth of the core-clock). See Table 11.33 for a description of the encoding of the clock ratio fields.

11.12.4 Adding Cycle Accurate Information to the Trace

Depending on the trace regeneration software, it is possible to obtain the exact cycle time relationship between each instruction in the trace. This information is added to the trace, when the $TCBCONTROLB_{CA}$ bit is set. The overhead on the trace information is a little more than one extra bit per core-clock cycle.

This setting only affects the TCB module and not the PDtrace module. The extra bit therefore only affects the likelihood of the TCB fifo overflowing.

11.13 TCB On-Chip Trace Memory

When on-chip trace memory is available ($TCBCONFIG_{OnT}$ is set) the memory is typically of smaller size than if it were external in a trace probe. The assumption is that it is of some value to trace a smaller piece of the program.

With on-chip trace memory, the TCB can work in three possible modes:

1. Trace-From mode.
2. Trace-To mode.
3. Under Trigger unit control.

Software can select this mode using the $TCBCONTROLB_{TM}$ field. If one or more trigger control registers ($TCBTRIGx$) are implemented, and they are using Start, End or About triggers, then the trace mode in $TCBCONTROLB_{TM}$ should be set to Trace-To mode.

11.13.1 On-Chip Trace Memory Size

The supported On-chip trace memory size can range from 256 byte to 8Mbytes, in powers of 2. The actual size is shown in the $TCBCONFIG_{SZ}$ field.

11.13.2 Trace-From Mode

In the Trace-From mode, tracing begins when the processor enters into a processor mode/ASID value which is defined to be traced or when an EJTAG hardware breakpoint trace trigger turns on tracing. Trace collection is stopped when the buffer is full. The TCB then signals buffer full using $TCBCONTROLB_{BF}$. When external software polling this register finds the $TCBCONTROLB_{BF}$ bit set, it can then read out the internal trace memory. Saving the trace into the internal buffer will re-commence again only when the $TCBCONTROLB_{BF}$ bit is reset and if the core is sending valid trace data (i.e., $PDO_IamTracing$ not equal 0).

11.13.3 Trace-To Mode

In the Trace-To mode, the TCB keeps writing into the internal trace memory, wrapping over and overwriting the oldest information, until the processor reaches an end of trace condition. End of trace is reached by leaving the processor mode/ASID value which is traced, or when an EJTAG hardware breakpoint trace trigger turns tracing off. At this

point, the on-chip trace buffer is then dumped out in a manner similar to that described above in [Section 11.13.2 “Trace-From Mode”](#).

24K® Processor Core Instructions

This chapter supplements the MIPS32 Architecture Reference Manual by describing instruction behavior that is specific to a 24K processor core. The chapter is divided *into* the following sections:

- [Section 12.1 “Understanding the Instruction Descriptions”](#)
- [Section 12.2 “24K® Opcode Map”](#)
- [Section 12.3 “Floating Point Unit Instruction Format Encodings”](#)
- [Section 12.4 “MIPS32® Instruction Set for the 24K® Core”](#)

The 24K processor core also supports the MIPS16e ASE to the MIPS32 architecture. The MIPS16e ASE instruction set is described in [Chapter 13, “MIPS16e™ Application-Specific Extension to the MIPS32® Instruction Set”](#) on page 349.

12.1 Understanding the Instruction Descriptions

Refer to Volume II of the *MIPS32 Architecture Reference Manual* [2] for more information about the instruction descriptions. There is a description of the instruction fields, definition of terms, and a description function notation available in that document.

12.2 24K® Opcode Map

Table 12.1 Symbols Used in the Instruction Encoding Tables

| Symbol | Meaning |
|----------|---|
| * | Operation or field codes marked with this symbol are reserved for future use, are valid encodings for a higher-order MIPS ISA level, or are part of an application specific extension not implemented on this core. Executing such an instruction will cause a Reserved Instruction Exception. |
| δ | (Also <i>italic</i> field name.) Operation or field codes marked with this symbol denotes a field class. The instruction word must be further decoded by examining additional tables that show values for another instruction field. |
| ∇ | Operation or field codes marked with this symbol represent instructions which are only legal if 64-bit floating point operations are enabled. In other cases, executing such an instruction will cause a Reserved Instruction Exception (non-coprocessor encodings or coprocessor instruction encodings for a coprocessor to which access is allowed) or a Coprocessor Unusable Exception (coprocessor instruction encodings for a coprocessor to which access is not allowed). |
| ϕ | Operation or field codes marked with this symbol are obsolete and will be removed from a future revision of the MIPS32 ISA. Software should avoid using these operation or field codes. |

Table 12.2 MIPS32 Encoding of the Opcode Field

| opcode | | bits 28..26 | | | | | | | |
|-------------|-----|-------------------------|------------------------|----------------------|--------------|--------------------------|-------------|--------------|--------------------------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 31..29 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | <i>SPECIAL</i> δ | <i>REGIMM</i> δ | J | JAL | BEQ | BNE | BLEZ | BGTZ |
| 1 | 001 | ADDI | ADDIU | SLTI | SLTIU | ANDI | ORI | XORI | LUI |
| 2 | 010 | <i>COP0</i> δ | <i>COP1</i> δ | <i>COP2</i> δ | <i>COP1X</i> | BEQL ϕ | BNEL ϕ | BLEZL ϕ | BGTZL ϕ |
| 3 | 011 | * | * | * | * | <i>SPECIAL2</i> δ | JALX | * | <i>SPECIAL3</i> δ |
| 4 | 100 | LB | LH | LWL | LW | LBU | LHU | LWR | * |
| 5 | 101 | SB | SH | SWL | SW | * | * | SWR | CACHE |
| 6 | 110 | LL | LWC1 | LWC2 | PREF | * | LDC1 | LDC2 | * |
| 7 | 111 | SC | SWC1 | SWC2 | * | * | SDC1 | SDC2 | * |

Table 12.3 MIPS32 *SPECIAL* Opcode Encoding of Function Field

| function | | bits 2..0 | | | | | | | |
|-----------|-----|------------------|-----------------------|---------------------|------|---------|-------|----------------------|------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 5..3 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | SLL ¹ | <i>MOVCI</i> δ | <i>SRL</i> δ | SRA | SLLV | * | <i>SRLV</i> δ | SRAV |
| 1 | 001 | JR ² | JALR ² | MOVZ | MOVN | SYSCALL | BREAK | * | SYNC |
| 2 | 010 | MFHI | MTHI | MFLO | MTLO | * | * | * | * |
| 3 | 011 | MULT | MULTU | DIV | DIVU | * | * | * | * |
| 4 | 100 | ADD | ADDU | SUB | SUBU | AND | OR | XOR | NOR |
| 5 | 101 | * | * | SLT | SLTU | * | * | * | * |
| 6 | 110 | TGE | TGEU | TLT | TLTU | TEQ | * | TNE | * |
| 7 | 111 | * | * | * | * | * | * | * | * |

1. Specific encodings of the *rt*, *rd*, and *sa* fields are used to distinguish among the SLL, NOP, SSNOP, and EHB functions.
2. Specific encodings of the hint field are used to distinguish JR from JR.HB and JALR from JALR.HB

Table 12.4 MIPS32 *REGIMM* Encoding of *rt* Field

| rt | | bits 18..16 | | | | | | | |
|-------------|----|-------------|--------|----------------|----------------|------|-----|------|--------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 20..19 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | BLTZ | BGEZ | BLTZL ϕ | BGEZL ϕ | * | * | * | * |
| 1 | 01 | TGEI | TGEIU | TLTI | TLTIU | TEQI | * | TNEI | * |
| 2 | 10 | BLTZAL | BGEZAL | BLTZALL ϕ | BGEZALL ϕ | * | * | * | * |
| 3 | 11 | * | * | * | * | * | * | * | SYNCHI |

Table 12.5 MIPS32 *SPECIAL2* Encoding of Function Field

| function | | bits 2..0 | | | | | | | |
|-----------|-----|-----------|-------|-----|-----|------|-------|-----|-------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 5..3 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | MADD | MADDU | MUL | * | MSUB | MSUBU | * | * |
| 1 | 001 | * | * | * | * | * | * | * | * |
| 2 | 010 | CorExtend | | | | | | | |
| 3 | 011 | | | | | | | | |
| 4 | 100 | CLZ | CLO | * | * | * | * | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | * | * | * | * | SDBBP |

Table 12.6 MIPS32 *Special3* Encoding of Function Field for Release 2 of the Architecture

| function | | bits 2..0 | | | | | | | |
|-----------|-----|-----------------------|-----|-----|-------|-----|-----|-----|-----|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 5..3 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | EXT | * | * | * | INS | * | * | * |
| 1 | 001 | * | * | * | * | * | * | * | * |
| 2 | 010 | * | * | * | * | * | * | * | * |
| 3 | 011 | * | * | * | * | * | * | * | * |
| 4 | 100 | <i>BSHFL</i> δ | * | * | * | * | * | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | RDHWR | * | * | * | * |

Table 12.7 MIPS32 *MOVCI* Encoding of tf Bit

| tf | bit 16 | |
|----|--------|------|
| | 0 | 1 |
| | MOVF | MOVT |

Table 12.8 MIPS32 *SRL* Encoding of Shift/Rotate

| tf | bit 21 | |
|----|--------|------|
| | 0 | 1 |
| | SRL | ROTR |

Table 12.9 MIPS32 *SRLV* Encoding of Shift/Rotate

| tf | bit 6 | |
|----|-------|-------|
| | 0 | 1 |
| | SRLV | ROTRV |

Table 12.10 MIPS32 BSHFLEncoding of sa Field¹

| sa | | bits 8..6 | | | | | | | |
|------------|----|-----------|-----|------|-----|-----|-----|-----|-----|
| bits 10..9 | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | | | WSBH | | | | | |
| 1 | 01 | | | | | | | | |
| 2 | 10 | SEB | | | | | | | |
| 3 | 11 | SEH | | | | | | | |

1. The sa field is sparsely decoded to identify the final instructions. Entries in this table with no mnemonic are reserved for future use by MIPS Technologies and may or may not cause a Reserved Instruction exception.

Table 12.11 MIPS32 COP0 Encoding of rs Field

| rs | | bits 23..21 | | | | | | | |
|-------------|----|-------------|-----|--------|-----------------------------|------|-----|--------|-----|
| bits 25..24 | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | MFC0 | * | * | * | MTC0 | * | * | * |
| 1 | 01 | * | * | RDPGPR | <i>MFMC0</i> ¹ δ | * | * | WRPGPR | * |
| 2 | 10 | C0 δ | | | | | | | |
| 3 | 11 | | | | | | | | |

1. Release 2 of the Architecture added the MFMC0 function, which is further decoded as the DI and EI instructions.

Table 12.12 MIPS32COP0 Encoding of Function Field When rs=CO

| function | | bits 2..0 | | | | | | | |
|-----------|-----|-----------|------|-------|-----|-----|-----|-------|-------|
| bits 5..3 | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | * | TLBR | TLBWI | * | * | * | TLBWR | * |
| 1 | 001 | TLBP | * | * | * | * | * | * | * |
| 2 | 010 | * | * | * | * | * | * | * | * |
| 3 | 011 | ERET | * | * | * | * | * | * | DERET |
| 4 | 100 | WAIT | * | * | * | * | * | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | * | * | * | * | * |

Table 12.13 MIPS32 COP1 Encoding of rs Field

| rs | | <i>bits 23..21</i> | | | | | | | |
|--------------------|----|---------------------|-------------------|------|-------|-------------------|-------------------|------|-------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 25..24</i> | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | MFC1 | * | CFC1 | MFHC1 | MTC1 | * | CTC1 | MTHC1 |
| 1 | 01 | <i>BC1</i> δ | * | * | * | * | * | * | * |
| 2 | 10 | <i>S</i> δ | <i>D</i> δ | * | * | <i>W</i> δ | <i>L</i> δ | * | * |
| 3 | 11 | * | * | * | * | * | * | * | * |

Table 12.14 MIPS32 COP1 Encoding of Function Field When rs=S

| function | | <i>bits 2..0</i> | | | | | | | |
|------------------|-----|------------------|------------------|-----------------|------------------|---------|----------------|----------------|---------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 5..3</i> | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | ADD | SUB | MUL | DIV | SQRT | ABS | MOV | NEG |
| 1 | 001 | ROUND.L ∇ | TRUNC.L ∇ | CEIL.L ∇ | FLOOR.L ∇ | ROUND.W | TRUNC.W | CEIL.W | FLOOR.W |
| 2 | 010 | * | MOVCF δ | MOVZ | MOVN | * | RECIP ∇ | RSQRT ∇ | * |
| 3 | 011 | * | * | * | * | * | * | * | * |
| 4 | 100 | * | CVT.D | * | * | CVT.W | CVT.L ∇ | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | * | * | * | * | * |

Table 12.15 MIPS32 COP1 Encoding of Function Field When rs=D

| function | | <i>bits 2..0</i> | | | | | | | |
|------------------|-----|------------------|------------------|-----------------|------------------|---------|----------------|----------------|---------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 5..3</i> | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | ADD | SUB | MUL | DIV | SQRT | ABS | MOV | NEG |
| 1 | 001 | ROUND.L ∇ | TRUNC.L ∇ | CEIL.L ∇ | FLOOR.L ∇ | ROUND.W | TRUNC.W | CEIL.W | FLOOR.W |
| 2 | 010 | * | MOVCF δ | MOVZ | MOVN | * | RECIP ∇ | RSQRT ∇ | * |
| 3 | 011 | * | * | * | * | * | * | * | * |
| 4 | 100 | CVT.S | * | * | * | CVT.W | CVT.L ∇ | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | * | * | * | * | * |

Table 12.16 MIPS32 COP1 Encoding of Function Field When rs=W or L¹

| function | | <i>bits 2..0</i> | | | | | | | |
|------------------|-----|------------------|-------|-----|-----|-----|-----|-----|-----|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 5..3</i> | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | * | * | * | * | * | * | * | * |
| 1 | 001 | * | * | * | * | * | * | * | * |
| 2 | 010 | * | * | * | * | * | * | * | * |
| 3 | 011 | * | * | * | * | * | * | * | * |
| 4 | 100 | CVT.S | CVT.D | * | * | * | * | * | * |
| 5 | 101 | * | * | * | * | * | * | * | * |
| 6 | 110 | * | * | * | * | * | * | * | * |
| 7 | 111 | * | * | * | * | * | * | * | * |

1. Format type L is legal only if 64-bit floating point operations are enabled.

Table 12.17 MIPS32 COP1 Encoding of tf Bit When rs=S or D, Function=MOVCF

| tf | <i>bit 16</i> | |
|-----------|---------------|----------|
| | 0 | 1 |
| | MOVf.fmt | MOVT.fmt |

Table 12.18 MIPS64 COP1X Encoding of Function Field¹

| function | | <i>bits 2..0</i> | | | | | | | |
|------------------|-----|------------------|-----------|-----|-----|----------|---------|-----|---------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 5..3</i> | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 000 | LWXC1 ▽ | LDXC1 ▽ | * | * | * | LUXC1 ▽ | * | * |
| 1 | 001 | SWXC1 ▽ | SDXC1 ▽ | * | * | * | SUXC1 ▽ | * | PREFX ▽ |
| 2 | 010 | * | * | * | * | * | * | * | * |
| 3 | 011 | * | * | * | * | * | * | * | * |
| 4 | 100 | MADD.S ▽ | MADD.D ▽ | * | * | * | * | * | * |
| 5 | 101 | MSUB.S ▽ | MSUB.D ▽ | * | * | * | * | * | * |
| 6 | 110 | NMADD.S ▽ | NMADD.D ▽ | * | * | 24k * | * | * | * |
| 7 | 111 | NMSUB.S ▽ | NMSUB.D ▽ | * | * | * | * | * | * |

1. COP1X instructions are legal only if 64-bit floating point operations are enabled.

Table 12.19 MIPS32 COP2 Encoding of rs Field

| rs | <i>bits 23..21</i> | | | | | | | |
|--------------------|--------------------|------|-----|------|-------|------|-----|------|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <i>bits 25..24</i> | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | MFC2 | * | CFC2 | MFHC2 | MTC2 | * | CTC2 |
| 1 | 01 | BC2δ | * | * | * | * | * | * |
| 2 | 10 | C2 | | | | | | |
| 3 | 11 | | | | | | | |

12.3 Floating Point Unit Instruction Format Encodings

Instruction format encodings for the floating point unit are presented in this section. This information is a tabular presentation of the encodings described in tables [Table 12.13](#) and [Table 12.18](#) above.

Table 12.20 Floating Point Unit Instruction Format Encodings

| <i>fmt</i> field (bits 25..21 of COP1 opcode) | | <i>fmt3</i> field (bits 2..0 of COP1X opcode) | | Mnemonic | Name | Bit Width | Data Type |
|---|--------|---|------|---|---------------|-----------|----------------|
| Decimal | Hex | Decimal | Hex | | | | |
| 0..15 | 00..0F | — | — | Used to encode Coprocessor 1 interface instructions (MFC1, CTC1, etc.). Not used for format encoding. | | | |
| 16 | 10 | 0 | 0 | S | Single | 32 | Floating Point |
| 17 | 11 | 1 | 1 | D | Double | 64 | Floating Point |
| 18..19 | 12..13 | 2..3 | 2..3 | Reserved for future use by the architecture. | | | |
| 20 | 14 | 4 | 4 | W | Word | 32 | Fixed Point |
| 21 | 15 | 5 | 5 | L | Long | 64 | Fixed Point |
| 22 | 16 | 6 | 6 | PS | Paired Single | 2 × 32 | Floating Point |
| 23 | 17 | 7 | 7 | Reserved for future use by the architecture. | | | |
| 24..31 | 18..1F | — | — | Reserved for future use by the architecture. Not available for <i>fmt3</i> encoding. | | | |

12.4 MIPS32® Instruction Set for the 24K® Core

This section describes the MIPS32 instructions for the 24K cores. [Table 12.21](#) lists the instructions in alphabetical order. Instructions that have implementation dependent behavior are described afterwards. The descriptions for other instructions exist in the architecture reference manual and are not duplicated here.

Table 12.21 24K™ Core Instruction Set

| Instruction | Description | Function |
|-------------|--|--|
| ABS.fmt | Floating Point Absolute Value fmt = s,d | $Fd = \text{abs}(Fs)$ |
| ADD | Integer Add | $Rd = Rs + Rt$ |
| ADD.fmt | Floating Point Add fmt = s,d | $Fd = Fs + Ft$ |
| ADDI | Integer Add Immediate | $Rt = Rs + \text{Immed}$ |
| ADDIU | Unsigned Integer Add Immediate | $Rt = Rs +_U \text{Immed}$ |
| ADDIUPC | Unsigned Integer Add Immediate to PC (MIPS16 only) | $Rt = PC +_U \text{Immed}$ |
| ADDU | Unsigned Integer Add | $Rd = Rs +_U Rt$ |
| AND | Logical AND | $Rd = Rs \& Rt$ |
| ANDI | Logical AND Immediate | $Rt = Rs \& (0_{16} \parallel \text{Immed})$ |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|---|--|
| B | Unconditional Branch (Assembler idiom for: BEQ r0, r0, offset) | PC += (int)offset |
| BAL | Branch and Link (Assembler idiom for: BGEZAL r0, offset) | GPR[31] = PC + 8 PC += (int)offset |
| BC1F | Branch On Floating Point False | if (cc[i] == 0) then PC += (int)offset |
| BC1FL | Branch On Floating Point False Likely | if (cc[i] == 0) then PC += (int)offset else Ignore Next Instruction |
| BC1T | Branch On Floating Point True | if(cc[i] == 1) then PC += (int)offset |
| BC1TL | Branch On Floating Point True Likely | if (cc[i] == 1) then PC += (int)offset else Ignore Next Instruction |
| BC2F | Branch On CP2 False | if (cc[i] == 0) then PC += (int)offset |
| BC2FL | Branch On CP2 False Likely | if (cc[i] == 0) then PC += (int)offset else Ignore Next Instruction |
| BC2T | Branch On CP2 True | if(cc[i] == 1) then PC += (int)offset |
| BC2TL | Branch On CP2 True Likely | if (cc[i] == 1) then PC += (int)offset else Ignore Next Instruction |
| BEQ | Branch On Equal | if Rs == Rt PC += (int)offset |
| BEQL | Branch On Equal Likely | if Rs == Rt PC += (int)offset else Ignore Next Instruction |
| BGEZ | Branch on Greater Than or Equal To Zero | if !Rs[31] PC += (int)offset |
| BGEZAL | Branch on Greater Than or Equal To Zero And Link | GPR[31] = PC + 8 if !Rs[31] PC += (int)offset |
| BGEZALL | Branch on Greater Than or Equal To Zero And Link Likely | GPR[31] = PC + 8 if !Rs[31] PC += (int)offset else Ignore Next Instruction |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|--|---|
| BGEZL | Branch on Greater Than or Equal To Zero Likely | if !Rs[31] PC += (int)offset else Ignore Next Instruction |
| BGTZ | Branch on Greater Than Zero | if !Rs[31] && Rs != 0 PC += (int)offset |
| BGTZL | Branch on Greater Than Zero Likely | if !Rs[31] && Rs != 0 PC += (int)offset else Ignore Next Instruction |
| BLEZ | Branch on Less Than or Equal to Zero | if Rs[31] Rs == 0 PC += (int)offset |
| BLEZL | Branch on Less Than or Equal to Zero Likely | if Rs[31] Rs == 0 PC += (int)offset else Ignore Next Instruction |
| BLTZ | Branch on Less Than Zero | if Rs[31] PC += (int)offset |
| BLTZAL | Branch on Less Than Zero And Link | GPR[31] = PC + 8 if Rs[31] PC += (int)offset |
| BLTZALL | Branch on Less Than Zero And Link Likely | GPR[31] = PC + 8 if Rs[31] PC += (int)offset else Ignore Next Instruction |
| BLTZL | Branch on Less Than Zero Likely | if Rs[31] PC += (int)offset else Ignore Next Instruction |
| BNE | Branch on Not Equal | if Rs != Rt PC += (int)offset |
| BNEL | Branch on Not Equal Likely | if Rs != Rt PC += (int)offset else Ignore Next Instruction |
| BREAK | Breakpoint | Break Exception |
| C.cond.fmt | Floating Point Compare fmt = s,d | cc[i] = Fs compare_cond Ft |
| CACHE | Cache Operation | See Below |
| CEIL.L.fmt | Floating Point Ceiling to Long Fixed Point | Fd = convert_and_round(Fs) |
| CEIL.W.fmt | Floating Point Ceiling to Word Fixed Point | Fd = convert_and_round(Fs) |
| CFC1 | Move Control Word From Floating Point | Rt = FP_Control[Fs] |
| CFC2 | Move Control Word From CP2 | Rt = CP2_Control[Fs] |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|--|---|
| CLO | Count Leading Ones | $Rd = \text{NumLeadingOnes}(Rs)$ |
| CLZ | Count Leading Zeroes | $Rd = \text{NumLeadingZeroes}(Rs)$ |
| COP2 | Coprocessor 2 Operation | Implementation dependent |
| CTC1 | Move Control Word To Floating Point | $FP_Control[Fs] = Rt$ |
| CTC2 | Move Control Word to CP2 | $CP2_Control[Fs] = Rt$ |
| CVT.D.fmt | Floating Point Convert to Double Floating Point fmt = S,W,L | $Fd = \text{convert_and_round}(Fs)$ |
| CVT.D.fmt | Floating Point Convert to Double Floating Point fmt = S,W,L | $Fd = \text{convert_and_round}(Fs)$ |
| CVT.L.fmt | Floating Point Convert to Long Fixed Point fmt = S,D | $Fd = \text{convert_and_round}(Fs)$ |
| CVT.S.fmt | Floating Point Convert to Single Floating Point fmt = W,D,L | $Fd = \text{convert_and_round}(Fs)$ |
| CVT.W.fmt | Floating Point Convert to Word Fixed Point fmt = S,D | $Fd = \text{convert_and_round}(Fs)$ |
| DERET | Return from Debug Exception | $PC = DEPC$ Exit Debug Mode |
| DI | Atomically Disable Interrupts | $Rt = Status; Status_{IE} = 0$ |
| DIV | Divide | $LO = (int)Rs / (int)Rt$ $HI = (int)Rs \% (int)Rt$ |
| DIV.fmt | Floating Point Divide fmt = S,D | $Fd = Fs/Ft$ |
| DIVU | Unsigned Divide | $LO = (uns)Rs / (uns)Rt$ $HI = (uns)Rs \% (uns)Rt$ |
| EHB | Execution Hazard Barrier | Stop instruction execution until execution hazards are cleared |
| EI | Atomically Enable Interrupts | $Rt = Status; Status_{IE} = 1$ |
| ERET | Return from Exception | if $SR[2]$ $PC = ErrorEPC$ else $PC = EPC$ $SR[1] = 0$ $SR[2] = 0$ $LL = 0$ |
| EXT | Extract Bit Field | $Rt = \text{ExtractField}(Rs, pos, size)$ |
| FLOOR.L.fmt | Floating Point Floor to Long Fixed Point fmt = S,D | $Fd = \text{convert_and_round}(Fs)$ |
| FLOOR.W.fmt | Floating Point Floor to Word Fixed Point fmt = S,D | $Fd = \text{convert_and_round}(Fs)$ |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|--|---|
| INS | Insert Bit Field | $Rt = \text{InsertField}(Rs, Rt, pos, size)$ |
| J | Unconditional Jump | $PC = PC[31:28] \parallel offset \ll 2$ |
| JAL | Jump and Link | $GPR[31] = PC + 8$ $PC = PC[31:28] \parallel offset \ll 2$ |
| JALR | Jump and Link Register | $Rd = PC + 8$ $PC = Rs$ |
| JALR.HB | Jump and Link Register with Hazard Barrier | Like JALR, but also clears execution and instruction hazards |
| JALRC | Jump and Link Register Compact - do not execute instruction in jump delay slot (MIPS16 only) | $Rd = PC + 2$ $PC = Rs$ |
| JR | Jump Register | $PC = Rs$ |
| JR.HB | Jump Register with Hazard Barrier | Like JR, but also clears execution and instruction hazards |
| JRC | Jump Register Compact - do not execute instruction in jump delay slot (MIPS16 only) | $PC = Rs$ |
| LB | Load Byte | $Rt = (\text{byte})\text{Mem}[base+offset]$ |
| LBU | Unsigned Load Byte | $Rt = (\text{ubyte})\text{Mem}[base+offset]$ |
| LDC1 | Load Doubleword to Floating Point | $Ft = \text{memory}[base+offset]$ |
| LDC2 | Load Doubleword to CP2 | $Ft = \text{memory}[base+offset]$ |
| LDXC1 | Load Doubleword Indexed to Floating Point | $Fd = \text{memory}[base+index]$ |
| LH | Load Halfword | $Rt = (\text{half})\text{Mem}[base+offset]$ |
| LHU | Unsigned Load Halfword | $Rt = (\text{uhalf})\text{Mem}[base+offset]$ |
| LL | Load Linked Word | $Rt = \text{Mem}[base+offset]$ $LL = 1$ |
| LUI | Load Upper Immediate | $Rt = \text{immediate} \ll 16$ |
| LUXC1 | Load Doubleword Indexed Unaligned to Floating Point | $Fd = \text{memory}[(base+index)psize-1..3]$ |
| LW | Load Word | $Rt = \text{Mem}[Rs+offset]$ |
| LWC1 | Load Word to Floating Point | $Ft = \text{memory}[base+offset]$ |
| LWC2 | Load Word to CP2 | $Ft = \text{memory}[base+offset]$ |
| LWPC | Load Word, PC relative | $Rt = \text{Mem}[PC+offset]$ |
| LWXC1 | Load Word Indexed to Floating Point | $Fd = \text{memory}[base+index]$ |
| LWL | Load Word Left | See Architecture Reference Manual |
| LWR | Load Word Right | See Architecture Reference Manual |
| MADD | Multiply-Add | $HI \mid LO += (\text{int})Rs * (\text{int})Rt$ |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|---|-----------------------------------|
| MADD.fmt | Floating Point Multiply Add fmt = S,D | $Fd = Fs * Ft + Fr$ |
| MADDU | Multiply-Add Unsigned | $HI \mid LO += (uns)Rs * (uns)Rt$ |
| MFC0 | Move From Coprocessor 0 | $Rt = CPR[0, Rd, sel]$ |
| MFC1 | Move From FPR | $Rt = Fs_{31..0}$ |
| MFC2 | Move From CP2 Register | $Rt = Fs_{31..0}$ |
| MFHC1 | Move From High Half of FPR | $Rt = Fs_{63..32}$ |
| MFHC2 | Move From High Half of CP2 Register | $Rt = Fs_{63..32}$ |
| MFHI | Move From HI | $Rd = HI$ |
| MFLO | Move From LO | $Rd = LO$ |
| MOV.fmt | Floating Point Move | $Fd = Fs$ |
| MOVF | GPR Conditional Move on Floating Point False | if $(cc[i] == 0)$ then $Rd = Rs$ |
| MOVF.fmt | FPR Conditional Move on Floating Point False | if $(cc[i] == 0)$ then $Fd = Fs$ |
| MOVN | GPR Conditional Move on Not Zero | if $Rt \neq 0$ then $Rd = Rs$ |
| MOVN.fmt | FPR Conditional Move on Not Zero | if $Rt \neq 0$ then $Fd = Fs$ |
| MOVT | GPR Conditional Move on Floating Point True | if $(cc[i] == 1)$ then $Rd = Rs$ |
| MOVT.fmt | FPR Conditional Move on Floating Point True | if $(cc[i] == 1)$ then $Fd = Fs$ |
| MOVZ | GPR Conditional Move on Zero | if $Rt = 0$ then $Rd = Rs$ |
| MOVZ.fmt | FPR Conditional Move on Zero | if $(Rt == 0)$ then $Fd = Fs$ |
| MSUB | Multiply-Subtract | $HI \mid LO -= (int)Rs * (int)Rt$ |
| MSUB.fmt | Floating Point Multiply Subtract fmt = S,D | $Fd = Fs * Ft - Fr$ |
| MSUBU | Multiply-Subtract Unsigned | $HI \mid LO -= (uns)Rs * (uns)Rt$ |
| MTC0 | Move To Coprocessor 0 | $CPR[0, n, Sel] = Rt$ |
| MTC1 | Move To FPR | $Fs = Rt$ |
| MTC2 | Move to CP2 register | $Fs = Rt$ |
| MTHC1 | Move To High Half of FPR | $Fd = Rt \mid\mid Fs_{31..0}$ |
| MTHC2 | Move to High Half of CP2 register | $Fd = Rt \mid\mid Fs_{31..0}$ |
| MTHI | Move To HI | $HI = Rs$ |
| MTLO | Move To LO | $LO = Rs$ |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|--|---|
| MUL | Multiply with register write | HI LO =Unpredictable $Rd = ((int)Rs * (int)Rt)_{31..0}$ |
| MUL.fmt | Floating Point Multiply fmt = S,D | $Fd = Fs * Ft$ |
| MULT | Integer Multiply | HI LO = $(int)Rs * (int)Rd$ |
| MULTU | Unsigned Multiply | HI LO = $(uns)Rs * (uns)Rd$ |
| NEG.fmt | Floating Point Negate fmt = S,D | $Fd = neg(Fs)$ |
| NMADD.fmt | Floating Point Negative Multiply Add fmt = S,D | $Fd = neg(Fs * Ft + Fr)$ |
| NMSUB.fmt | Floating Point Negative Multiply Subtract fmt = S,D | $Fd = neg(Fs * Ft - Fr)$ |
| NOP | No Operation (Assembler idiom for: SLL r0, r0, r0) | |
| NOR | Logical NOR | $Rd = ~(Rs Rt)$ |
| OR | Logical OR | $Rd = Rs Rt$ |
| ORI | Logical OR Immediate | $Rt = Rs Immed$ |
| PREF | Prefetch | Load Specified Line into Cache |
| PREFX | Prefetch Indexed | Load Specified Line into Cache |
| RDHWR | Read Hardware Register | Allows unprivileged access to registers enabled by <i>HWREna</i> register |
| RDPGPR | Read GPR from Previous Shadow Set | $Rt = SGPR[SRSCtl_{PSS}, Rd]$ |
| RECIP.fmt | Floating Point Reciprocal Approximation fmt = S,D | $Fd = recip(Fs)$ |
| RESTORE | Restore registers and deallocate stack frame (MIPS16 only) | See Architecture Reference Manual |
| ROTR | Rotate Word Right | $Rd = Rt_{sa-1..0} Rt_{31..sa}$ |
| ROTRV | Rotate Word Right Variable | $Rd = Rt_{Rs-1..0} Rt_{31..Rs}$ |
| ROUND.L.fmt | Floating Point Round to Long Fixed Point fmt = S,D | $Fd = convert_and_round(Fs)$ |
| ROUND.W.fmt | Floating Point Round to Word Fixed Point fmt = S,D | $Fd = convert_and_round(Fs)$ |
| RSQRT.fmt | Floating Point Reciprocal Square Root Approximation fmt = S,D | $Fd = rsqrt(Fs)$ |
| SAVE | Save registers and allocate stack frame (MIPS16 only) | See Architecture Reference Manual |
| SB | Store Byte | $(byte)Mem[base+offset] = Rt$ |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|---|---|
| SC | Store Conditional Word | if LL = 1 mem[base+offset] = Rt Rt = LL |
| SDBBP | Software Debug Break Point | Trap to SW Debug Handler |
| SDC1 | Store Doubleword from Floating Point | memory[base+offset] = Ft |
| SDC2 | Store Doubleword from CP2 | memory[base+offset] = Ft |
| SDXC1 | Store Word Indexed from Floating Point | memory[base+index] = Fs |
| SEB | Sign Extend Byte | Rd = (byte)Rs |
| SEH | Sign Extend Half | Rd = (half)Rs |
| SH | Store Half | (half)Mem[base+offset] = Rt |
| SLL | Shift Left Logical | Rd = Rt << sa |
| SLLV | Shift Left Logical Variable | Rd = Rt << Rs[4:0] |
| SLT | Set on Less Than | if (int)Rs < (int)Rt Rd = 1 else Rd = 0 |
| SLTI | Set on Less Than Immediate | if (int)Rs < (int)Immed Rt = 1 else Rt = 0 |
| SLTIU | Set on Less Than Immediate Unsigned | if (uns)Rs < (uns)Immed Rt = 1 else Rt = 0 |
| SLTU | Set on Less Than Unsigned | if (uns)Rs < (uns)Immed Rd = 1 else Rd = 0 |
| SQRT.fmt | Floating Point Square Root fmt = S,D | Fd = sqrt(Fs) |
| SRA | Shift Right Arithmetic | Rd = (int)Rt >> sa |
| SRAV | Shift Right Arithmetic Variable | Rd = (int)Rt >> Rs[4:0] |
| SRL | Shift Right Logical | Rd = (uns)Rt >> sa |
| SRLV | Shift Right Logical Variable | Rd = (uns)Rt >> Rs[4:0] |
| SSNOP | Superscalar Inhibit No Operation | NOP |
| SUB | Integer Subtract | Rt = (int)Rs - (int)Rd |
| SUB.fmt | Floating Point Subtract fmt = S,D | Fd = Fs - Ft |
| SUBU | Unsigned Subtract | Rt = (uns)Rs - (uns)Rd |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|---|---|
| SUXC1 | Store Doubleword Indexed Unaligned from Floating Point | memory[(base+index)psize-1..3] = Fs |
| SW | Store Word | Mem[base+offset] = Rt |
| SWC1 | Store Word From Floating Point | Mem[base+offset] = Fs |
| SWC2 | Store Word From CP2 Register | Mem[base+offset] = Fs |
| SWL | Store Word Left | See Architecture Reference Manual |
| SWR | Store Word Right | See Architecture Reference Manual |
| SWXC1 | Store Word Indexed to Floating Point | memory[base+index] = Fs |
| SYNC | Synchronize | See Below |
| SYNCHI | Synchronize Caches to Make Instruction Writes Effective | For D-cache writeback and I-cache invalidate on specified address |
| SYSCALL | System Call | SystemCallException |
| TEQ | Trap if Equal | if Rs == Rt TrapException |
| TEQI | Trap if Equal Immediate | if Rs == (int)Immed TrapException |
| TGE | Trap if Greater Than or Equal | if (int)Rs >= (int)Rt TrapException |
| TGEI | Trap if Greater Than or Equal Immediate | if (int)Rs >= (int)Immed TrapException |
| TGEIU | Trap if Greater Than or Equal Immediate Unsigned | if (uns)Rs >= (uns)Immed TrapException |
| TGEU | Trap if Greater Than or Equal Unsigned | if (uns)Rs >= (uns)Rt TrapException |
| TLBWI | Write Indexed TLB Entry | See Below |
| TLBWR | Write Random TLB Entry | See Below |
| TLBP | Probe TLB for Matching Entry | See Architecture Reference Manual |
| TLBR | Read Index for TLB Entry | See Below |
| TLT | Trap if Less Than | if (int)Rs < (int)Rt TrapException |
| TLTI | Trap if Less Than Immediate | if (int)Rs < (int)Immed TrapException |
| TLTIU | Trap if Less Than Immediate Unsigned | if (uns)Rs < (uns)Immed TrapException |
| TLTU | Trap if Less Than Unsigned | if (uns)Rs < (uns)Rt TrapException |
| TNE | Trap if Not Equal | if Rs != Rt TrapException |

Table 12.21 24K™ Core Instruction Set (Continued)

| Instruction | Description | Function |
|-------------|---|---|
| TNEI | Trap if Not Equal Immediate | if Rs != (int)Immed TrapException |
| TRUNC.L.fmt | Floating Point Truncate to Long Fixed Point | Fd = convert_and_round(Fs) |
| TRUNC.W.fmt | Floating Point Truncate to Word Fixed Point | Fd = convert_and_round(Fs) |
| WAIT | Wait for Interrupts | Stall until interrupt occurs |
| WRPGPR | Write to GPR in Previous Shadow Set | SGPR[SRSCtl _{PSS} , Rd] = Rt |
| WSBH | Word Swap Bytes Within HalfWords | Rd = Rt _{23..16} Rt _{31..24} Rt _{7..0} Rt _{15..8} |
| XOR | Exclusive OR | Rd = Rs ^ Rt |
| XORI | Exclusive OR Immediate | Rt = Rs ^ (uns)Immed |
| ZEB | Zero extend byte (MIPS16 only) | Rt = (ubyte) Rs |
| ZEH | Zero extend half (MIPS16 only) | Rt = (uhalf) Rs |

Table 12.22 List of instructions in the MIPS32® DSP ASE in the Arithmetic sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|--------------------|--------------------|------------------------------|---------------|--|
| ADDQ.PH rd,rs,rt ADDQ_S.PH rd,rs,rt | Pair Q15 | Pair Q15 | GPR | VoIP SoftM | Element-wise addition of two vectors of Q15 fractional values, with optional saturation. |
| ADDQ_S.W rd,rs,rt | Q31 | Q31 | GPR | Audio | Add two Q31 fractional values with saturation. |
| ADDU.QB rd,rs,rt ADDU_S.QB rd,rs,rt | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Video | Element-wise addition of vectors of four unsigned byte values. Results may be optionally saturated to 255. |
| SUBQ.PH rd,rs,rt SUBQ_S.PH rd,rs,rt | Pair Q15 | Pair Q15 | GPR | VoIP | Element-wise subtraction of two vectors of Q15 fractional values, with optional saturation. |
| SUBQ_S.W rd,rs,rt | Q31 | Q31 | GPR | Audio | Subtraction with Q31 fractional values, with saturation. |
| SUBU.QB rd,rs,rt SUBU_S.QB rd,rs,rt | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Video | Element-wise subtraction of unsigned byte values, with optional unsigned saturation. |
| ADDSC rd,rs,rt | Signed Word | Signed Word | GPR & DSPControl | Audio | Add two signed words and set the carry bit in the DSPControl register. |
| ADDWC rd,rs,rt | Signed Word | Signed Word | GPR | Audio | Add two signed words with the carry bit from the DSPControl register. |

Table 12.22 List of instructions in the MIPS32® DSP ASE in the Arithmetic sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|--------------------|-----------------------|------------------------------|------|---|
| MODSUB rd,rs,rt | Signed Word | Signed Word | GPR | Misc | Modulo addressing support: update a byte index into a circular buffer by subtracting a specified decrement (in bytes) from the index, resetting the index to a specified value if the subtraction results in underflow. |
| RADDU.W.QB rd,rs | Quad Unsigned Byte | Unsigned Word | GPR | Misc | Reduce (add together) the 4 unsigned byte values in <i>rs</i> , zero-extending the sum to 32 bits before writing to the destination register. For example, if all 4 input values are 0x80 (decimal 128), then the result in <i>rd</i> is 0x200 (decimal 512). |
| ABSQ_S.PH rd,rt | Pair Q15 | Pair Q15 | GPR | Misc | Find the absolute value of each of two Q15 fractional halfword elements in the source register, saturating values of -1.0 to the maximum positive Q15 fractional value. |
| ABSQ_S.W rd,rt | Q31 | Q31 | GPR | Misc | Find the absolute value of the Q31 fractional element in the source register, saturating the value -1.0 to the maximum positive Q31 fractional value. |
| PRECRQ.QB.PH rd,rs,rt | 2 Pair Q15 | Quad Byte | GPR | Misc | Reduce the precision of four Q15 fractional input values by truncation to create four Q7 fractional output values. The two Q15 values from register <i>rs</i> are written to the two left-most byte results, allowing an endian-agnostic implementation. |
| PRECR_SRA.PH.W rt,rs,sa PRECR_SRA_R.PH.W rt,rs,sa | Two Integer Words | Pair Integer Halfword | GPR | Misc | Reduce the precision of two integer word values to create a pair of integer halfword values. Each word value is first shifted right arithmetically by <i>sa</i> bit positions, and optionally rounded up by adding 1 at the most-significant discard bit position. The 16 least-significant bits of each word are then written to the corresponding halfword elements of destination register <i>rt</i> . |
| PRECRQ.PH.W rd,rs,rt PRECRQ_RS.PH.W rd,rs,rt | 2 Q31 | Pair half-word | GPR | Misc | Reduce the precision of two Q31 fractional input values by truncation to create two Q15 fractional output values. The Q15 value obtained from register <i>rs</i> creates the left-most result, allowing an endian-agnostic implementation. Results may be optionally rounded up and saturated before being written to the destination. |
| PRECRQU_S.QB.PH rd,rs,rt | 2 Pair Q15 | Quad Unsigned Byte | GPR | Misc | Reduce the precision of four Q15 fractional values by saturating and truncating to create four unsigned byte values. |

Table 12.22 List of instructions in the MIPS32® DSP ASE in the Arithmetic sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|-----------------|-------------------|------------------------------|-------|--|
| PRECEQ.W.PHL rd,rt PRECEQ.W.PHR rd,rt | Q15 | Q31 | GPR | Misc | Expand the precision of a Q15 fractional value to create a Q31 fractional value by adding 16 least-significant bits to the input value. |
| PRECEQU.PH.QBL rd,rt PRECEQU.PH.QBR rd,rt PRECEQU.PH.QBLA rd,rt PRECEQU.PH.QBRA rd,rt | Unsigned Byte | Q15 | GPR | Video | Expand the precision of two unsigned byte values by prepending a sign bit and adding seven least-significant bits to each to create two Q15 fractional values. |
| PRECEU.PH.QBL rd,rt PRECEU.PH.QBR rd,rt PRECEU.PH.QBLA rd,rt PRECEU.PH.QBRA rd,rt | Unsigned Byte | Unsigned halfword | GPR | Video | Expand the precision of two unsigned byte values by adding eight least-significant bits to each to create two unsigned halfword values. |

Table 12.23 List of instructions in the MIPS32® DSP ASE in the GPR-Based Shift sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|----------------------|----------------------|------------------------------|-------|--|
| SHLL.QB rd, rt, sa SHLLV.QB rd, rt, rs | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Misc | Element-wise left shift of eight signed bytes. Zeros are inserted into the bits emptied by the shift. The shift amount is specified by the three least-significant bits of <i>sa</i> or <i>rs</i> . |
| SHLL.PH rd, rt, sa SHLLV.PH rd, rt, rs SHLL_S.PH rd, rt, sa SHLLV_S.PH rd, rt, rs | Pair Signed halfword | Pair Signed halfword | GPR | Misc | Element-wise left shift of two signed halfwords, with optional saturation on overflow. Zeros are inserted into the bits emptied by the shift. The shift amount is specified by the four least-significant bits of <i>sa</i> or <i>rs</i> . |
| SHLL_S.W rd, rt, sa SHLLV_S.W rd, rt, rs | Signed Word | Signed Word | GPR | Misc | Left shift of a signed word, with saturation on overflow. Zeros are inserted into the bits emptied by the shift. The shift amount is specified by the five least-significant bits of <i>sa</i> or <i>rs</i> . Use the MIPS32 instructions SLL or SLLV for non-saturating shift operations. |
| SHRL.QB rd, rt, sa SHRLV.QB rd, rt, rs | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Video | Element-wise logical right shift of four byte values. Zeros are inserted into the bits emptied by the shift. The shift amount is specified by the three least-significant bits of <i>sa</i> or <i>rs</i> . |
| SHRA.PH rd, rt, sa SHRAV.PH rd, rt, rs SHRA_R.PH rd, rt, sa SHRAV_R.PH rd, rt, rs | Pair Signed halfword | Pair Signed halfword | GPR | Misc | Element-wise arithmetic (sign preserving) right shift of two halfword values. Optionally, rounding may be performed, adding 1 at the most-significant discard bit position. The shift amount is specified by the four least-significant bits of <i>rs</i> or by the argument <i>sa</i> . |

Table 12.23 List of instructions in the MIPS32® DSP ASE in the GPR-Based Shift sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|---|-----------------|------------------|------------------------------|-------|---|
| SHRA_R.W rd, rt, sa SHRAV_R.W rd, rt, rs | Signed Word | Signed Word | GPR | Video | Arithmetic (sign preserving) right shift of a word value. Optionally, rounding may be performed, adding 1 at the most-significant discard bit position. The shift amount is specified by the five least-significant bits of <i>rs</i> or the argument <i>sa</i> . |

Table 12.24 List of instructions in the MIPS32® DSP ASE in the Multiply sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|---|------------------------|------------------------------|-------------|--|
| MULEU_S.PH.QBL rd,rs,rt MULEU_S.PH.QBR rd,rs,rt | Pair Unsigned Byte, Pair Unsigned Halfword, | Pair Unsigned Halfword | GPR | Still Image | Element-wise multiplication of two unsigned byte values from register <i>rs</i> with two unsigned halfword values from register <i>rt</i> . Each 24-bit product is truncated to 16 bits, with saturation if the product exceeds 0xFFFF, and written to the corresponding element in the destination register. |
| MULQ_RS.PH rd,rs,rt | Pair Q15 | Pair Q15 | GPR | Misc | Element-wise multiplication of two Q15 fractional values to create two Q15 fractional results, with rounding and saturation. After multiplication, each 32-bit product is rounded up by adding 0x00008000, then truncated to create a Q15 fractional value that is written to the destination register. If both multiplicands are -1.0, the result is saturated to the maximum positive Q15 fractional value. To stay compliant with the base architecture, this instruction leaves the base <i>HI-LO</i> pair UNPREDICTABLE after the operation. The other DSP ASE accumulators <i>ac1-ac3</i> are untouched. |
| MULEQ_S.W.PHL rd,rs,rt MULEQ_S.W.PHR rd,rs,rt | Pair Q15 | Q31 | GPR | VoIP | Multiplication of two Q15 fractional values, shifting the product left by 1 bit to create a Q31 fractional result. If both multiplicands are -1.0 the result is saturated to the maximum positive Q31 value. To stay compliant with the base architecture, this instruction leaves the base <i>HI-LO</i> pair UNPREDICTABLE after the operation. The other DSP ASE accumulators <i>ac1-ac3</i> must be untouched. |

Table 12.24 List of instructions in the MIPS32® DSP ASE in the Multiply sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--------------------------|-----------------|------------------|------------------------------|--------------|--|
| DPAU.H.QBL DPAU.H.QBR | Pair Bytes | Halfword | Acc | Image | Dot-product accumulation. Two pairs of corresponding unsigned byte elements from source registers <i>rt</i> and <i>rs</i> are separately multiplied, and the two 16-bit products are then summed together. The summed products are then added to the accumulator. |
| DPSU.H.QBL DPSU.H.QBR | Pair Bytes | Halfword | Acc | Image | Dot-product subtraction. Two pairs of corresponding unsigned byte elements from source registers <i>rt</i> and <i>rs</i> are separately multiplied, and the two 16-bit products are then summed together. The summed products are then subtracted from the accumulator. |
| DPAQ_S.W.PH ac,rs,rt | Pair Q15 | Q32.31 | ac | VoIP / SoftM | Dot-product accumulation. Two pairs of corresponding Q15 fractional values from source registers <i>rt</i> and <i>rs</i> are separately multiplied and left-shifted 1 bit to create two Q31 fractional products. For each product, if both multiplicands are equal to -1.0 the product is clamped to the maximum positive Q31 fractional value. The products are then summed, and the sum is then sign extended to the width of the accumulator and accumulated into the specified accumulator. This instruction may be used to compute the imaginary component of a 16-bit complex multiplication operation after first swapping the operands to place them in the correct order. |
| DPSQ_S.W.PH ac,rs,rt | Pair Q15 | Q32.31 | ac | VoIP / SoftM | Dot-product subtraction. Two pairs of corresponding Q15 fractional values from source registers <i>rt</i> and <i>rs</i> are separately multiplied and left-shifted 1 bit to create two Q31 fractional products. For each product, if both multiplicands are equal to -1.0 the product is clamped to the maximum positive Q31 fractional value. The products are then summed, and the sum is then sign extended to the width of the accumulator and subtracted from the specified accumulator. This instruction may be used to compute the imaginary component of a 16-bit complex multiplication operation after first swapping the operands to place them in the correct order. |

Table 12.24 List of instructions in the MIPS32® DSP ASE in the Multiply sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|-----------------|------------------|------------------------------|--------|--|
| MULSAQ_S.W.PH ac,rs,rt | Pair Q15 | Q32.31 | ac | SoftM | Complex multiplication step. Performs element-wise fractional multiplication of the two Q15 fractional values from registers <i>rt</i> and <i>rs</i> , subtracting one product from the other to create a Q31 fractional result that is added to accumulator <i>ac</i> . The intermediate products are saturated to the maximum positive Q31 fractional value if both multiplicands are equal to -1.0. |
| DPAQ_SA.L.W ac,rs,rt | Q31 | Q63 | ac | Audio | Fractional multiplication of two Q31 fractional values to produce a Q63 fractional product. If both multiplicands are -1.0 the product is saturated to the maximum positive Q63 fractional value. The product is then added to accumulator <i>ac</i> . If the addition results in overflow or underflow, the accumulator is saturated to the maximum positive or minimum negative value. |
| DPSQ_SA.L.W ac,rs,rt | Q31 | Q63 | ac | Audio | Fractional multiplication of two Q31 fractional values to produce a Q63 fractional product. If both multiplicands are -1.0 the product is saturated to the maximum positive Q63 fractional value. The product is then subtracted from accumulator <i>ac</i> . If the addition results in overflow or underflow, the accumulator is saturated to the maximum positive or minimum negative value. |
| MAQ_S.W.PHL ac,rs,rt MAQ_S.W.PHR ac,rs,rt | Q15 | Q32.31 | ac | SoftM | Fractional multiply-accumulate. The product of two Q15 fractional values is sign extended to the width of the accumulator and added to accumulator <i>ac</i> . The intermediate product is saturated to the maximum positive Q31 fractional value if both multiplicands are equal to -1.0. |
| MAQ_SA.W.PHL ac,rs,rt MAQ_SA.W.PHR ac,rs,rt | Q15 | Q31 | ac | speech | Fractional multiply-accumulate with saturation after accumulation. The product of two Q15 fractional values is sign extended to the width of the accumulator and added to accumulator <i>ac</i> . The intermediate product is saturated to the maximum positive Q31 fractional value if both multiplicands are equal to -1.0. If the accumulation results in overflow or underflow, the accumulator value is saturated to the maximum positive or minimum negative Q31 fractional value. |
| MADD, MADDU, MSUB, MSUBU, MULT, MULTU | Word | Double-Word | ac | Misc | Allows these instructions to target accumulators ac1, ac2, and ac3 (in addition to the original ac0 destination). |

Table 12.25 List of instructions in the MIPS32® DSP ASE in the Bit/ Manipulation sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|----------------------------------|-----------------|----------------------|------------------------------|--------------|---|
| BITREV rd,rt | Unsigned Word | Unsigned Word | GPR | Audio / FFT | Reverse the order of the 16 least-significant bits of register <i>rt</i> , writing the result to register <i>rd</i> . The 16 most-significant bits are set to zero. |
| INSV rt,rs | Unsigned Word | Unsigned Word | GPR | Misc | Like the Release 2 INS instruction, except that the 5 bits for <i>pos</i> and <i>size</i> values are obtained from the <i>DSPControl</i> register. <i>size</i> = <i>scount</i> [14:10], and <i>pos</i> = <i>pos</i> [20:16]. |
| REPL.QB rd,imm REPLV.QB rd,rt | Byte | Quad Byte | GPR | Video / Misc | Replicate a signed byte value into the four byte elements of register <i>rd</i> . The byte value is given by the 8 least-significant bits of the specified 10-bit immediate constant or by the 8 least-significant bits of register <i>rt</i> . |
| REPL.PH rd,imm REPLV.PH rd,rt | Signed halfword | Pair Signed halfword | GPR | Misc | Replicate a signed halfword value into the two halfword elements of register <i>rd</i> . The halfword value is given by the 16 least-significant bits of register <i>rt</i> , or by the value of the 10-bit immediate constant, sign-extended to 16 bits. |

Table 12.26 List of instructions in the MIPS32® DSP ASE in the Compare-Pick sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|----------------------|----------------------|------------------------------|-------|--|
| CMPU.EQ.QB rs,rt CMPU.LT.QB rs,rt CMPU.LE.QB rs,rt | Quad Unsigned Byte | Quad Unsigned Byte | DSPControl | Video | Element-wise unsigned comparison of the four unsigned byte elements of <i>rs</i> and <i>rt</i> , recording the boolean comparison results to the four right-most bits in the <i>ccond</i> field of the <i>DSPControl</i> register. |
| CMPGU.EQ.QB rd,rs,rt CMPGU.LT.QB rd,rs,rt CMPGU.LE.QB rd,rs,rt | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Video | Element-wise unsigned comparison of the four right-most unsigned byte elements of <i>rs</i> and <i>rt</i> , recording the boolean comparison results to the four least-significant bits of register <i>rd</i> . |
| CMP.EQ.PH rs,rt CMP.LT.PH rs,rt CMP.LE.PH rs,rt | Pair Signed halfword | Pair Signed halfword | DSPControl | Misc | Element-wise signed comparison of the two halfword elements of <i>rs</i> and <i>rt</i> , recording the boolean comparison results to the two right-most bits in the <i>ccond</i> field of the <i>DSPControl</i> register. |

Table 12.26 List of instructions in the MIPS32® DSP ASE in the Compare-Pick sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|-----------------------|-----------------------|----------------------|------------------------------|-------|--|
| PICK.QB rd,rs,rt | Quad Unsigned Byte | Quad Unsigned Byte | GPR | Video | Element-wise selection of unsigned bytes from the four bytes of registers <i>rs</i> and <i>rt</i> into the corresponding elements of register <i>rd</i> , based on the value of the four right-most bits of the <i>ccond</i> field in the <i>DSPControl</i> register. If the corresponding <i>ccond</i> bit is 1, the byte value is copied from register <i>rs</i> , otherwise it is copied from <i>rt</i> . |
| PICK.PH rd,rs,rt | Pair Signed halfword | Pair Signed halfword | GPR | Misc | Element-wise selection of signed halfwords from the two halfwords in registers <i>rs</i> and <i>rt</i> into the corresponding elements of register <i>rd</i> , based on the value of the two right-most bits of the <i>ccond</i> field in the <i>DSPControl</i> register. If the corresponding <i>ccond</i> bit is 1, the halfword value is copied from register <i>rs</i> , otherwise it is copied from <i>rt</i> . |
| PACKRL.PH rd,rs,rt | Pair Signed Halfwords | Pair Signed Halfword | GPR | Misc | Pack two halfwords taken from registers <i>rs</i> and <i>rt</i> into destination register <i>rd</i> . |

Table 12.27 List of instructions in the MIPS32® DSP ASE in the Accumulator and DSPControl Access sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|---|-----------------|------------------|------------------------------|------|--|
| EXTR.W rt,ac,shift EXTR_R.W rt,ac,shift EXTR_RS.W rt,ac,shift | Q63 | Q31 | GPR | Misc | Extract a Q31 fractional value from the 32 least-significant bits of 64-bit accumulator <i>ac</i> . The accumulator value may be shifted right logically by <i>shift</i> bits prior to the extraction, and the extracted value may be optionally rounded or rounded and saturated before being written to register <i>rt</i> . The <i>shift</i> argument value ranges from 0 to 31. The optional rounding step adds 1 at the most-significant bit position discarded by the shift. The optional saturation clamps the extracted value to the maximum positive Q31 value if the rounding step results in overflow. |

Table 12.27 List of instructions in the MIPS32® DSP ASE in the Accumulator and DSPControl Access sub-class (Continued)

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|-----------------|------------------|------------------------------|------|---|
| EXTR_S.H <i>rt,ac,shift</i> | Q63 | Q15 | GPR | Misc | Extract a Q15 fractional value from the 16 least-significant bits of 64-bit accumulator <i>ac</i> . The accumulator value may be shifted right logically by <i>shift</i> bits prior to the extraction, and the extracted value is saturated before being written to register <i>rt</i> . The <i>shift</i> argument value ranges from 0 to 31. The saturation clamps the extracted value to the maximum positive or minimum negative Q15 value if the shifted accumulator value cannot be represented accurately as a Q15 format value. |
| EXTRV_S.H <i>rt,ac,rs</i> | Q63 | Q15 | GPR | Misc | Extract a Q15 fractional value from the 16 least-significant bits of 64-bit accumulator <i>ac</i> . The accumulator value may be shifted right logically by <i>shift</i> bits prior to the extraction, and the extracted value is saturated before being written to register <i>rt</i> . The <i>shift</i> argument ranges from 0 to 31 and is given by the five least-significant bits of register <i>rs</i> . The saturation clamps the extracted value to the maximum positive or minimum negative Q15 value if the shifted accumulator value cannot be represented accurately as a Q15 format value. |
| EXTRV.W <i>rt,ac,rs</i> EXTRV_R.W <i>rt,ac,rs</i> EXTRV_RS.W <i>rt,ac,rs</i> | Q63 | Q31 | GPR | Misc | Extract a Q31 fractional value from the 32 least-significant bits of 64-bit accumulator <i>ac</i> . The accumulator value may be shifted right logically by <i>shift</i> bits prior to the extraction, and the extracted value may be optionally rounded or rounded and saturated before being written to register <i>rt</i> . The <i>shift</i> argument value is provided by the five least-significant bits of <i>rs</i> and ranges from 0 to 31. The optional rounding step adds 1 at the most-significant bit position discarded by the shift. The optional saturation clamps the extracted value to the maximum positive Q31 value if the rounding step results in overflow. |

Table 12.27 List of instructions in the MIPS32® DSP ASE in the Accumulator and DSPControl Access sub-class (Continued)

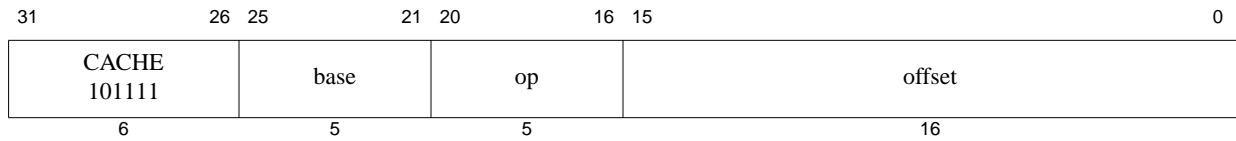
| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|--|-----------------|------------------|------------------------------|---------------|---|
| EXTP <i>rt,ac,size</i> EXTPV <i>rt,ac,rs</i> EXTPDP <i>rt,ac,size</i> EXTPDPV <i>rt,ac,rs</i> | Unsigned DWord | Unsigned Word | GPR / <i>DSPControl</i> | Audio / Video | <p>Extract a set of <i>size</i>+1 contiguous bits from accumulator <i>ac</i>, right-justifying and sign-extending the result to 32 bits before writing the result to register <i>rt</i>.</p> <p>The position of the left-most bit to extract is given by the value of the <i>pos</i> field in the <i>DSPControl</i> register (see Appendix C, “Endian-Agnostic Reference to Register Elements” on page 427 for details). The number of bits (less one) to extract is provided either by the <i>size</i> immediate operand or by the five least-significant bits of <i>rs</i>.</p> <p>The EXTPDP and EXTPDPV instructions also decrement the <i>pos</i> field by <i>size</i>+1 to facilitate sequential bit field extraction operations.</p> |
| SHILO <i>ac,shift</i> SHILOV <i>ac,rs</i> | Unsigned DWord | Unsigned DWord | ac | Misc | <p>Shift accumulator <i>ac</i> left or right by the specified number of bits, writing the shifted value back to the accumulator. The signed shift argument is specified either by the immediate operand <i>shift</i> or by the six least-significant bits of register <i>rs</i>. A negative shift argument results in a right shift of up to 32 bits, and a positive shift argument results in a left shift of up to 31 bits.</p> |
| MTHLIP <i>rs, ac</i> | Unsigned Word | Unsigned Word | ac / <i>DSPControl</i> | Audio / Video | <p>Copy the <i>LO</i> register of the specified accumulator to the <i>HI</i> register, copy <i>rs</i> to <i>LO</i>, and increment the <i>pos</i> field in <i>DSPControl</i> by 32.</p> |
| MFHI/MFLO/MTHI/MTLO | Unsigned Word | Unsigned Word | GPR/ac | Misc | <p>Copy an unsigned word to or from the specified accumulator <i>HI</i> or <i>LO</i> register to the specified GPR.</p> |
| WRDSP <i>rt,mask</i> | Unsigned Word | Unsigned Word | <i>DSPControl</i> | Misc | <p>Overwrite specific fields in the <i>DSPControl</i> register using the corresponding bits from the specified GPR. Bits in the <i>mask</i> argument correspond to specific fields in <i>DSPControl</i>; a value of 1 causes the corresponding <i>DSPControl</i> field to be overwritten using the corresponding bits in <i>rt</i>, otherwise the field is unchanged.</p> |
| RDDSP <i>rt,mask</i> | Unsigned Word | Unsigned Word | GPR | Misc | <p>Copy the values of specific fields in the <i>DSPControl</i> register to the specified GPR. Bits in the <i>mask</i> argument correspond to specific fields in <i>DSPControl</i>; a value of 1 causes the corresponding <i>DSPControl</i> field to be copied to the corresponding bits in <i>rt</i>, otherwise the bits in <i>rt</i> are unchanged.</p> |

Table 12.28 List of instructions in the MIPS32™ DSP ASE in the Indexed-Load sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|-----------------------|-----------------|------------------|------------------------------|------|--|
| LBUX rd,index(base) | - | Unsigned byte | GPR | Misc | Index byte load from address base+(index). Loads the byte in the low-order bits of the destination register and zero-extends the result. |
| LHX rd,index(base) | - | Signed halfword | GPR | Misc | Index halfword load from address base+(index). Loads the halfword in the low-order bits of the register and sign-extends the result. |
| LWX rd, index(base) | - | Signed Word | GPR | Misc | Indexed word load from address base+(index). |

Table 12.29 List of instructions in the MIPS32® DSP ASE in the Branch sub-class

| Instruction Mnemonics | Input Data Type | Output Data Type | Writes GPR / ac / DSPControl | App | Description |
|-----------------------|-----------------|------------------|------------------------------|---------------|--|
| BPOSGE32 offset | - | - | - | Audio / Video | Branch if the <i>pos</i> value is greater than or equal to integer 32. |



Format: CACHE op, offset(base)

MIPS32

Purpose: Perform Cache Operation

To perform the cache operation specified by op.

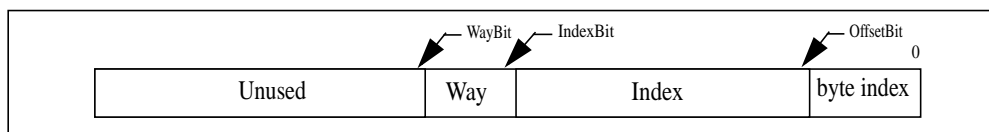
Description:

The 16-bit offset is sign-extended and added to the contents of the base register to form an effective address. The effective address is used in one of the following ways based on the operation to be performed and the type of cache as described in the following table.

Table 12.1 Usage of Effective Address

| Operation Requires an | Type of Cache | Usage of Effective Address |
|-----------------------|---------------|---|
| Address | Physical | The effective address is translated by the MMU to a physical address. The physical address is then used to address the cache |
| Index | N/A | <p>The effective address is used to index the cache.</p> <p>Assuming that the total cache size in bytes is CS, the associativity is A, and the number of bytes per tag is BPT, the following calculations give the fields of the address which specify the way and the index:</p> $\begin{aligned} \text{OffsetBit} &\leftarrow \text{Log2}(\text{BPT}) \\ \text{IndexBit} &\leftarrow \text{Log2}(\text{CS} / \text{A}) \\ \text{WayBit} &\leftarrow \text{IndexBit} + \text{Ceiling}(\text{Log2}(\text{A})) \\ \text{Way} &\leftarrow \text{Addr}_{\text{WayBit}-1..\text{IndexBit}} \\ \text{Index} &\leftarrow \text{Addr}_{\text{IndexBit}-1..\text{OffsetBit}} \end{aligned}$ |

Figure 12.1 Usage of Address Fields to Select Index and Way



A TLB Refill and TLB Invalid (both with cause code equal TLBL) exception can occur on any operation. For index operations (where the address is used to index the cache but need not match the cache tag) software should use unmapped addresses to avoid TLB exceptions. This instruction never causes TLB Modified exceptions nor TLB Refill exceptions with a cause code of TLBS.

The effective address may be an arbitrarily-aligned by address. The CACHE instruction never causes an Address Error Exception due to a non-aligned address.

A Cache Error exception may occur as a by-product of some operations performed by this instruction. For example, if a Writeback operation detects a cache or bus error during the processing of the operation, that error is reported via a Cache Error exception. Similarly, a Bus Error Exception may occur if a bus operation invoked by this instruction is terminated in an error. However, cache error exceptions should not be triggered by an Index Load Tag or Index Store

Tag operation, as these operations are used for initialization and diagnostic purposes.

An address Error Exception (with cause code equal AdEL) occurs if the effective address references a portion of the kernel address space which would normally result in such an exception.

Bits [17:16] of the instruction specify the cache on which to perform the operation, as follows:

Table 12.2 Encoding of Bits[17:16] of CACHE Instruction

| Code | Name | Cache | Cop0 Registers Used |
|------|------|--------------------------|----------------------------------|
| 2#00 | I | Primary Instruction | ITagLo, IDataLo, IDataHi, ErrCtl |
| 2#01 | D | Primary Data | DTagLo, DDataLo, ErrCtl |
| 2#10 | T | Tertiary - Not supported | |
| 2#11 | S | Secondary | L23TagLo, L23DataLo, L23DataHi |

Some of the operations use coprocessor0 registers as either sources or destinations. Each of the caches has a separate set of Tag and Data registers. The last column in [Table 12.4](#) lists which registers are used by operations to each cache. In the description of the operations, these may be explicitly listed or referred to in general, such as *xTagLo*, which would refer to the TagLo register corresponding to that cache.

Bits [20:18] of the instruction specify the operation to perform. On Index Load Tag and Index Store Data operations, the specific word (primary D) or double-word (primary I, secondary) that is addressed is loaded into / read from the *DDataLo* (primary D), *L23DataLo* and *L23DataHi* (secondary), or *IDataLo* and *IDataHi* (primary I) registers. All other cache instructions are line-based and the word and byte indexes will not affect their operation.

Table 12.3 Encoding of Bits [20:18] of the CACHE Instruction, ErrCtl[WST,SPR] Cleared

| Code | Caches | Name | Effective Address Operand Type | Operation | Implemented? |
|-------|---------|----------------------------|--------------------------------|---|--------------|
| 2#000 | I | Index Invalidate | Index | Set the state of the cache line at the specified index to invalid. This encoding may be used by software to invalidate the entire instruction cache by stepping through all valid indices. | Yes |
| | D, S, T | Index Writeback Invalidate | Index | If the state of the cache line at the specified index is valid and dirty, write the line back to the memory address specified by the cache tag. After that operation is completed, set the state of the cache line to invalid. If the line is valid but not dirty, set the state of the line to invalid. This encoding may be used by software to invalidate the entire data cache by stepping through all valid indices. Note that Index Store Tag should be used to initialize the cache at powerup. | Yes |

Table 12.3 Encoding of Bits [20:18] of the CACHE Instruction, ErrCtl[WST,SPR] Cleared (Continued)

| Code | Caches | Name | Effective Address Operand Type | Operation | Implemented? |
|-------|--------|------------------|--------------------------------|---|--------------|
| 2#001 | I | Index Load Tag | Index | <ul style="list-style-type: none"> Read the tag for the cache line at the specified index into the <i>TagLo0</i> Coprocessor 0 register. Read the data corresponding to the dword index into the <i>DataLo0</i> and <i>DataHi0</i> registers. Precode bits and data array parity bits are also read into the <i>ErrCtl</i> register. | Yes |
| 2#001 | D | Index Load Tag | Index | <ul style="list-style-type: none"> Read the tag for the cache line at the specified index into the <i>TagLo0</i> Coprocessor 0 register. Read the data corresponding to the word index into the <i>DataLo1</i> register. Data array parity bits are also read into the <i>ErrCtl</i> register. | Yes |
| 2#001 | S | Index Load Tag | Index | <ul style="list-style-type: none"> Read the tag for the cache line at the specified index into the <i>TagLo2</i> Coprocessor 0 register. Read the data corresponding to the dword index into the <i>L23DataLo</i> and <i>L23DataHi</i> registers. | Yes |
| 2#010 | All | Index Store Tag | Index | <p>Write the tag for the cache line at the specified index from the associated <i>TagLoN</i> Coprocessor 0 register.</p> <p>By default, the tag parity value will be automatically calculated. For test purposes, the parity/ECC bits from the <i>TagLoN</i> register will be used if <i>ErrCtl_{PO}</i> is set.</p> <p>This encoding may be used by software to initialize the entire instruction or data caches by stepping through all valid indices. Doing so requires that the <i>TagLo</i> register associated with the cache be initialized first.</p> | Yes |
| 2#011 | I,D,T | Reserved | Unspecified | Executed as a no-op | No |
| 2#011 | S | Index Store Data | Index | <p>Write the <i>L23DataHi</i> and <i>L23DataLo</i> Coprocessor 0 register contents at the way and dword index specified.</p> <p>The ECC bits are always generated by the hardware (if present)</p> | Yes |

Table 12.3 Encoding of Bits [20:18] of the CACHE Instruction, ErrCtl[WST,SPR] Cleared (Continued)

| Code | Caches | Name | Effective Address Operand Type | Operation | Implemented? |
|-------|---------|--------------------------|--------------------------------|--|--------------|
| 2#100 | All | Hit Invalidate | Address | If the cache line contains the specified address, set the state of the cache line to invalid. This encoding may be used by software to invalidate a range of addresses from the instruction cache by stepping through the address range by the line size of the cache. | Yes |
| 2#101 | I | Fill | Address | Fill the cache from the specified address. The cache line is refetched even if it is already in the cache. | Yes |
| | D, S, T | Hit WriteBack Invalidate | Address | If the cache line contains the specified address and it is valid and dirty, write the contents back to memory. After that operation is completed, set the state of the cache line to invalid. If the line is valid but not dirty, set the state of the line to invalid. This encoding may be used by software to invalidate a range of addresses from the data cache by stepping through the address range by the line size of the cache. | Yes |
| 2#110 | D, S, T | Hit WriteBack | Address | If the cache line contains the specified address and it is valid and dirty, write the contents back to memory. After the operation is completed, leave the state of the line valid, but clear the dirty state. | Yes |
| 2#111 | All | Fetch and Lock | Address | If the cache does not contain the specified address, fill it from memory, performing a writeback if required, and set the state to valid and locked. If the cache already contains the specified address, set the state to locked. The way selected on fill from memory is the least recently used. The lock state is cleared by executing an Index Invalidate, Index Writeback Invalidate, Hit Invalidate, or Hit Writeback Invalidate operation to the locked line, or via an Index Store Tag operation with the lock bit reset in the <i>xTagLo</i> register. It is illegal to lock all ways at a given cache index. If all ways are locked, subsequent references to that index will displace one of the locked lines. | Yes |

Table 0-1 Encoding of Bits [20:18] of the CACHE Instruction, ErrCtl[WST] Set. ErrCtl[SPR] Cleared

| Code | Caches | Name | Effective Address Operand Type | Operation | Implemented? |
|------------|--------|------------------|--------------------------------|---|--------------|
| 2#001 | All | Index Load WS | Index | Read the WS RAM at the specified index into the <i>xTagLo</i> Coprocessor 0 register. | Yes |
| 2#010 | I | Index Store WS | Index | Update the WS RAM at the specified index from the <i>ITagLo</i> Coprocessor 0 register. | Yes |
| 2#010 | D | Index Store WS | Index | Update the WS RAM at the specified index from the <i>DTagLo</i> Coprocessor 0 register. If <i>ErrCtl_{PO}</i> is set, the dirty parity values in the <i>DTagLo</i> register will be written to the WS RAM. Otherwise, the parity will be calculated for the write data. | Yes |
| 2#010 | S | Index Store WS | Index | Update the WS RAM at the specified index from the <i>L23TagLo</i> Coprocessor 0 register. If <i>ErrCtl_{PO}</i> is set, the dirty parity values in the <i>L23TagLo</i> register will be written to the WS RAM. Otherwise, the parity will be calculated for the write data. | Yes |
| 2#011 | I | Index Store Data | Index | Write the <i>IDataHi</i> and <i>IDataLo</i> Coprocessor 0 register contents at the way and dword index specified. If <i>ErrCtl_{PO}</i> is set, <i>ErrCtl_{PI}</i> is used for the parity value. Otherwise, the parity value is calculated for the write data. If <i>ErrCtl_{PCO}</i> is set, <i>ErrCtl_{PCI}</i> is used for the precode values. Otherwise, the precode values will be calculated based on the write data. | Yes |
| 2#011 | D | Index Store Data | Index | Write the <i>DDataLo</i> Coprocessor 0 register contents at the way and word index specified. If <i>ErrCtl_{PO}</i> is set, <i>ErrCtl_{PD}</i> is used for the parity value. Otherwise, the parity value is calculated for the write data. | Yes |
| 2#011 | S | Index Store ECC | Index | Write the <i>DDataLo</i> Coprocessor 0 register contents to the ECC bits at the way and dword index specified. | Yes |
| All Others | All | | | Other codes should not be used while ErrCtl _{WST} is set. | |

Table 12.4 Encoding of Bits [20:18] of the CACHE Instruction, ErrCtl[SPR] Set, ErrCtl[WST] Cleared

| Code | Caches | Name | Effective Address Operand Type | Operation | Implemented? |
|------------|--------|------------------|--------------------------------|--|--------------|
| 2#001 | I | Index Load Tag | Index | Read the SPRAM tag at the specified index into the <i>ITagLo</i> Coprocessor 0 register. Also read the instruction data and precode information corresponding to the byte index into the <i>IDataHi</i> , <i>IDataLo</i> , and <i>ErrCtl</i> registers | Yes |
| 2#001 | D | Index Load Tag | Index | Read the SPRAM tag at the specified index into the <i>DTagLo</i> Coprocessor 0 register. | Yes |
| 2#010 | I, D | Index Store Tag | Index | Update the SPRAM tag at the specified index from the <i>xTagLo</i> Coprocessor 0 register. | Yes |
| 2#011 | I | Index Store Data | Index | Write the <i>IDataLo</i> and <i>IDataHi</i> Coprocessor 0 register contents into the SPRAM at the dword index specified. | Yes |
| 2#011 | D | Index Store Data | Index | Write the <i>DDataLo</i> Coprocessor 0 register contents into the SPRAM at the word index specified. | Yes |
| All Others | I,D | | | Other codes should not be used while ErrCtl _{SPR} is set. | |
| All | S,T | | | Secondary and Tertiary operations should not be performed while ErrCtl _{SPR} is set. | |

Restrictions:

The operation of this instruction is **UNDEFINED** for any operation/cache combination that is not implemented.

The operation of this instruction is **UNDEFINED** if the operation requires an address, and that address is uncachable.

If access to Coprocessor 0 is not enabled, a Coprocessor Unusable Exception is signaled.

Operation:

```

vAddr ← GPR[base] + sign_extend(offset)
(pAddr, uncached) ← AddressTranslation(vAddr, DataReadReference)
CacheOp(op, vAddr, pAddr)

```

Exceptions:

TLB Refill Exception.

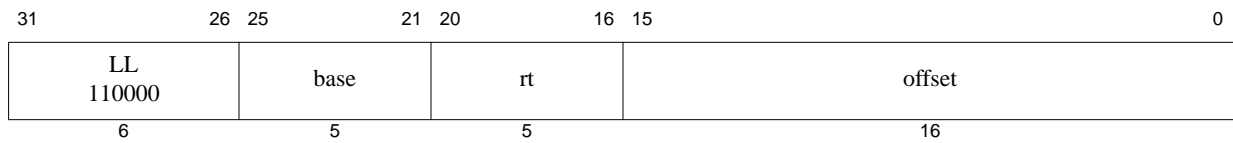
TLB Invalid Exception

Coprocessor Unusable Exception

Address Error Exception

Cache Error Exception

Bus Error Exception



Format: LL *rt*, *offset*(*base*)

MIPS32

Purpose: Load Linked Word

To load a word from *memory* for an atomic read-modify-write

Description: $GPR[rt] \leftarrow memory[GPR[base] + offset]$

The LL and SC instructions provide the primitives to implement atomic read-modify-write (RMW) operations for synchronizable memory locations.

The contents of the 32-bit word at the memory location specified by the aligned effective address are fetched and written into GPR *rt*. The 16-bit signed *offset* is added to the contents of GPR *base* to form an effective address.

This begins a RMW sequence on the current processor. There can be only one active RMW sequence per processor. When an LL is executed it starts an active RMW sequence replacing any other sequence that was active. The RMW sequence is completed by a subsequent SC instruction that either completes the RMW sequence atomically and succeeds, or does not and fails.

Executing LL on one processor does not cause an action that, by itself, causes an SC for the same block to fail on another processor.

An execution of LL does not have to be followed by execution of SC; a program is free to abandon the RMW sequence without attempting a write.

Restrictions:

The addressed location must be synchronizable by all processors and I/O devices sharing the location; if it is not, the result is **UNPREDICTABLE**. Which storage is synchronizable is a function of both CPU and system implementations. See the documentation of the SC instruction for the formal definition.

The effective address must be naturally-aligned. If either of the 2 least-significant bits of the effective address is non-zero, an Address Error exception occurs.

Operation:

```

vAddr ← sign_extend(offset) + GPR[base]
if vAddr1..0 ≠ 02 then
    SignalException(AddressError)
endif
(pAddr, CCA) ← AddressTranslation (vAddr, DATA, LOAD)
memword ← LoadMemory (CCA, WORD, pAddr, vAddr, DATA)
GPR[rt] ← memword
LLbit ← 1

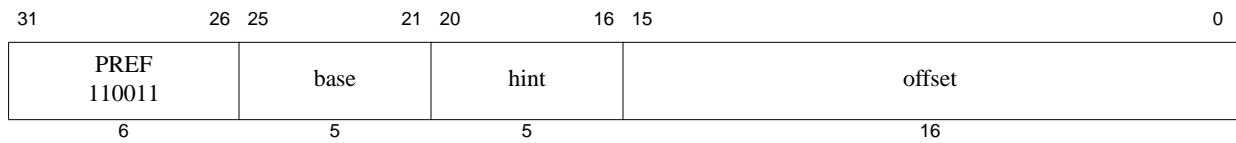
```

Exceptions:

TLB Refill, TLB Invalid, Address Error, Reserved Instruction, Watch

Programming Notes:

There is no Load Linked Word Unsigned operation corresponding to Load Word Unsigned.



Format: `PREF hint,offset(base)`

MIPS32

Purpose: Prefetch

To move data between memory and cache.

Description: `prefetch_memory(GPR[base] + offset)`

PREF adds the 16-bit signed *offset* to the contents of GPR *base* to form an effective byte address. The *hint* field supplies information about the way that the data is expected to be used.

PREF is an advisory instruction that may change the performance of the program. However, for all *hint* values except for PrepareForStore, and all effective addresses, it neither changes the architecturally visible state nor does it alter the meaning of the program.

PREF does not cause addressing-related exceptions, including TLB exceptions. If the address specified would cause an addressing exception, the exception condition is ignored and no data movement occurs. However even if no data is moved, some action that is not architecturally visible, such as writeback of a dirty cache line, can take place.

It is implementation-dependent whether a Bus Error or Cache Error exception is reported, when such an error is detected as a by-product of the action taken by the PREF instruction.

PREF neither generates a memory operation nor modifies the state of a cache line for a location with an *uncached* memory access type, whether this type is specified by the address segment (e.g., *kseg1*), the programmed coherency attribute of a segment (e.g., the use of the K0, KU, or K23 fields in the *Config* register), or the per-page coherency attribute provided by the TLB.

If PREF results in a memory operation, the memory access type and coherency attribute used for the operation are determined by the memory access type and coherency attribute of the effective address, just as it would be if the memory operation had been caused by a load or store to the effective address.

Any of the following conditions causes the core to treat a PREF instruction as a NOP.

- A reserved *hint* value is used
- The address has a translation error
- The address maps to an uncacheable page

In all other cases, except when *hint* equals 25, execution of the PREF instruction initiates an external bus read transaction. PREF is a non-blocking operation and does not cause the pipeline to stall while waiting for the data to be returned.

Table 12.1 Values of *hint* Field for PREF Instruction

| Value | Name | Data Use and Desired Prefetch Action |
|-------|-------|---|
| 0 | load | Use: Prefetched data is expected to be read (not modified). Action: Fetch data as if for a load. |
| 1 | store | Use: Prefetched data is expected to be stored or modified. Action: Fetch data as if for a store. |

Table 12.1 Values of *hint* Field for PREF Instruction

| | | |
|-------|--|---|
| 2-3 | Reserved | Reserved - treated as a NOP. |
| 4 | load_streamed | Use: Prefetched data is expected to be read (not modified) but not reused extensively; it “streams” through cache. Action: Fetch data as if for a store. LRU replacement information is ignored and data is placed in way 0 of the cache, so it will be displaced by other streamed prefetches and not displace retained prefetches. If way 0 is locked, the prefetch will be dropped. |
| 5 | store_streamed | Use: Prefetched data is expected to be stored or modified but not reused extensively; it “streams” through cache. Action: Fetch data as if for a store. LRU replacement information is ignored and data is placed in way 0 of the cache, so it will be displaced by other streamed prefetches and not displace retained prefetches. If way 0 is locked, the prefetch will be dropped. |
| 6 | load_retained | Use: Prefetched data is expected to be read (not modified) and reused extensively; it should be “retained” in the cache. Action: Fetch data as if for a load. LRU replacement information is used, but way 0 of the cache is specifically excluded. This prevents streamed prefetches from displacing the line. |
| 7 | store_retained | Use: Prefetched data is expected to be stored or modified and reused extensively; it should be “retained” in the cache. Action: Fetch data as if for a store. LRU replacement information is used, but way 0 of the cache is specifically excluded. This prevents streamed prefetches from displacing the line. |
| 8-24 | Reserved | Reserved - treated as a NOP. |
| 25 | writeback_invalidate (also known as “nudge”) | Use: Data is no longer expected to be used. Action: Schedule a writeback of any dirty data. The cache line is marked as invalid upon completion of the writeback. If cache line is clean or locked, no action is taken. |
| 26-29 | Reserved | Reserved - treated as a NOP. |
| 30 | PrepareForStore | Use: Prepare the cache for writing an entire line, without the overhead involved in filling the line from memory. Action: If the reference hits in the cache, no action is taken. If the reference misses in the cache, a line is selected for replacement, any valid and dirty victim is written back to memory, the entire line is filled with zero data, and the state of the line is marked as valid and dirty. Programming Note: Because the cache line is filled with zero data only on a cache miss, software must not assume that this action, in and of itself, can be used as a fast bzero-type function. |
| 31 | Reserved | Reserved - treated as a NOP. |

Restrictions:

None

Operation:

```

vAddr ← GPR[base] + sign_extend(offset)
(pAddr, CCA) ← AddressTranslation(vAddr, DATA, LOAD)

```

```
Prefetch(CCA, pAddr, vAddr, DATA, hint)
```

Exceptions:

Bus Error, Cache Error

Prefetch does not take any TLB-related or address-related exceptions under any circumstances.

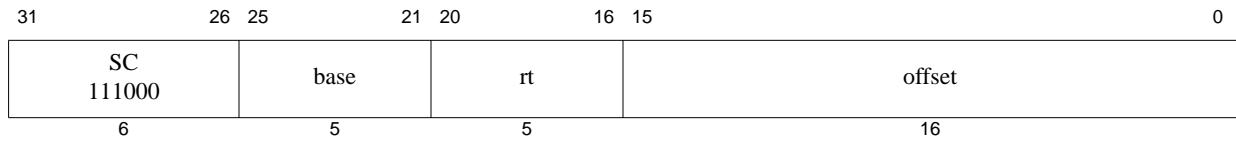
Programming Notes:

Prefetch cannot move data to or from a mapped location unless the translation for that location is present in the TLB. Locations in memory pages that have not been accessed recently may not have translations in the TLB, so prefetch may not be effective for such locations.

Prefetch does not cause addressing exceptions. A prefetch may be used using an address pointer before the validity of the pointer is determined without worrying about an addressing exception.

It is implementation dependent whether a Bus Error or Cache Error exception is reported if such an error is detected as a by-product of the action taken by the PREF instruction. Typically, this only occurs in systems which have high-reliability requirements.

Prefetch operations have no effect on cache lines that were previously locked with the CACHE instruction.



Format: SC *rt*, *offset*(*base*)

MIPS32

Purpose: Store Conditional Word

To store a word to memory to complete an atomic read-modify-write

Description: if `atomic_update` then `memory[GPR[base] + offset] ← GPR[rt]`, `GPR[rt] ← 1`
 else `GPR[rt] ← 0`

The LL and SC instructions provide primitives to implement atomic read-modify-write (RMW) operations for synchronizable memory locations.

The 32-bit word in GPR *rt* is conditionally stored in memory at the location specified by the aligned effective address. The 16-bit signed *offset* is added to the contents of GPR *base* to form an effective address.

The SC completes the RMW sequence begun by the preceding LL instruction executed on the processor. To complete the RMW sequence atomically, the following occur:

- The 32-bit word of GPR *rt* is stored into memory at the location specified by the aligned effective address.
- A 1, indicating success, is written into GPR *rt*.

Otherwise, memory is not modified and a 0, indicating failure, is written into GPR *rt*.

If any of the following events occurs between the execution of LL and SC, the SC fails:

- An ERET instruction is executed.

If either of the following events occurs between the execution of LL and SC, the SC may succeed or it may fail; the success or failure is not predictable. Portable programs should not cause one of these events.

- A memory access instruction (load, store, or prefetch) is executed on the processor executing the LL/SC.
- The instructions executed starting with the LL and ending with the SC do not lie in a 2048-byte contiguous region of virtual memory. (The region does not have to be aligned, other than the alignment required for instruction words.)

The following conditions must be true or the result of the SC is **UNPREDICTABLE**:

- Execution of SC must have been preceded by execution of an LL instruction.
- An RMW sequence executed without intervening events that would cause the SC to fail must use the same address in the LL and SC. The address is the same if the virtual address, physical address, and cache-coherence algorithm are identical.

Restrictions:

The effective address must be naturally-aligned. If either of the 2 least-significant bits of the address is non-zero, an Address Error exception occurs.

Operation:

$\text{vAddr} \leftarrow \text{sign_extend}(\text{offset}) + \text{GPR}[\text{base}]$

```

if vAddr1..0 ≠ 02 then
    SignalException(AddressError)
endif
(pAddr, CCA) ← AddressTranslation (vAddr, DATA, STORE)
dataword ← GPR[rt]
if LLbit then
    StoreMemory (CCA, WORD, dataword, pAddr, vAddr, DATA)
endif
GPR[rt] ← 031 || LLbit

```

Exceptions:

TLB Refill, TLB Invalid, TLB Modified, Address Error, Watch

Programming Notes:

LL and SC are used to atomically update memory locations, as shown below.

```

L1:
    LL      T1, (T0)  # load counter
    ADDI    T2, T1, 1 # increment
    SC      T2, (T0)  # try to store, checking for atomicity
    BEQ     T2, 0, L1 # if not atomic (0), try again
    NOP                                # branch-delay slot

```

Exceptions between the LL and SC cause SC to fail, so persistent exceptions must be avoided. Some examples of these are arithmetic operations that trap, system calls, and floating point operations that trap or require software emulation assistance.

LL and SC function on a single processor for *cached noncoherent* memory so that parallel programs can be run on uniprocessor systems that do not support *cached coherent* memory access types.

| | | | | | | | | | | | |
|-------------------|----|----|--------------------------|----|----|----|-------|----|----------------|---|---|
| 31 | 26 | 25 | 21 | 20 | 16 | 15 | 11 | 10 | 6 | 5 | 0 |
| SPECIAL 000000 | | | 0 00 0000 0000 0000 0 | | | | stype | | SYNC 001111 | | |
| 6 | | | 15 | | | | 5 | | 6 | | |

Format: SYNC (stype = 0 implied)

MIPS32

Purpose: To order loads and stores for shared memory.

Description:

These types of ordering guarantees are available through the SYNC instruction:

- Completion Barriers
- Ordering Barriers

Simple Description for Completion Barrier:

- The specified memory instructions (loads or stores or both) that occur before the SYNC instruction must be completed before the specified memory instructions after the SYNC are allowed to start.
- Loads are completed when the destination register is written. Stores are completed when the stored value is visible to every other processor in the system.

Detailed Description for Completion Barrier:

- Every synchronizable specified memory instruction (loads or stores or both) that occurs in the instruction stream before the SYNC instruction must be already globally performed before any synchronizable specified memory instruction that occurs after the SYNC are allowed to be performed, with respect to any other processor or coherent I/O module.
- The barrier does not guarantee the order in which instruction fetches are performed.
- A stype value of zero will always be defined such that it performs the most complete set of synchronization operations that are defined. This means stype zero always does a completion barrier that affects both loads and stores preceding the SYNC instruction and both loads and stores that are subsequent to the SYNC instruction. Non-zero values of stype may be defined by the architecture or specific implementations to perform synchronization behaviors that are less complete than that of stype zero. If an implementation does not use one of these non-zero values to define a different synchronization behavior, then that non-zero value of stype must act the same as stype zero completion barrier. This allows software written for an implementation with a lighter-weight barrier to work on another implementation which only implements the stype zero completion barrier.
- A completion barrier is required, potentially in conjunction with SSNOP (in Release 1 of the Architecture) or EHB (in Release 2 of the Architecture), to guarantee that memory reference results are visible across operating mode changes. For example, a completion barrier is required on entry to and exit from Debug Mode to guarantee that memory affects are handled correctly.

Completion Barrier Types:

All completion barrier types will flush any pending writes and potentially generate an external SYNC request. An

external SYNC request will be sent if $Config7_{ES} = 1$ and $SI_SyncTxEn = 1$. The first term is a software enable for externalizing SYNCs and the second term is a hardware enable, indicating that the next level device (L2 or system) supports SYNC transactions. The core will wait for all pending reads to complete as well as the SYNC response if it was externalized.

- 0x2 - Implementation specific style. Intervention SYNC. When coherence is enabled, this SYNC will generate a CoherentSync request. The CoherenceManager will respond to the SYNC when the interventions for all older coherent requests have been completed. If coherence is not enabled, will default to type 0x0.
- 0x3 - Implementation specific style. Memory SYNC. When coherence is enabled, this SYNC will also generate a CoherentSync request. When interventions for all older coherent requests have completed, the sync will be sent to memory interface unit. All pending transactions will be sent out. If the next level device (L2 or system) supports legacy SYNC transactions, as indicated by $SyncTxEn = 1$, an external SYNC request will also be generated. The CM will send a response to the core when all prior requests have completed and a SYNC response is received (if it was externalized).
- 0x0 - If coherence is enabled, this will be mapped to either a type 0x2 or 0x3 based on the value of the SYN-CCTL bit in the CM Control GCR. If coherence is not enabled, a legacy SYNC request will be generated. This will bypass the intervention pipeline in the CM and go directly to the memory unit. If $SyncTxEn = 1$, an external SYNC request will be generated.

Simple Description for Ordering Barrier:

- The specified memory instructions (loads or stores or both) that occur before the SYNC instruction must always be ordered before the specified memory instructions after the SYNC.
- Memory instructions which are ordered before other memory instructions are processed by the load/store datapath first before the other memory instructions.

Detailed Description for Ordering Barrier:

- Every synchronizable specified memory instruction (loads or stores or both) that occurs in the instruction stream before the SYNC instruction must reach a stage in the load/store datapath after which no instruction re-ordering is possible before any synchronizable specified memory instruction which occurs after the SYNC instruction in the instruction stream reaches the same stage in the load/store datapath.
- If any memory instruction before the SYNC instruction in program order, generates a memory request to the external memory and any memory instruction after the SYNC instruction in program order also generates a memory request to external memory, the memory request belonging to the older instruction must be globally performed before the time the memory request belonging to the younger instruction is globally performed.
- The barrier does not guarantee the order in which instruction fetches are performed.

As compared to the completion barrier, the ordering barrier is a lighter-weight operation as it does not require the specified instructions before the SYNC to be already completed. Instead it only requires that those specified instructions which are subsequent to the SYNC in the instruction stream are never re-ordered for processing ahead of the specified instructions which are before the SYNC in the instruction stream. This potentially reduces how many cycles the barrier instruction must stall before it completes.

The Acquire and Release barrier types are used to minimize the memory orderings that must be maintained and still have software synchronization work.

Because the core processes loads and stores in order, ordering barriers are much lighter weight. The core handles all ordering barriers identically. The LSU will complete any pending evictions and the BIU will stop merging on all WBB entries. No external request will be generated and the core will not wait for pending transactions to complete.

For the purposes of this description, the CACHE, PREF and PREFX instructions are treated as loads and stores. That is, these instructions and the memory transactions sourced by these instructions obey the ordering and completion rules of the SYNC instruction.

Table 12.1 lists the available completion barrier and ordering barriers behaviors that can be specified using the stype field..

Table 12.1 Encodings of the Bits[10:6] of the SYNC instruction; the STYPE Field

| Code | Name | Older instructions which must reach the load/store ordering point before the SYNC instruction completes. | Younger instructions which must reach the load/store ordering point only after the SYNC instruction completes. | Older instructions which must be globally performed when the SYNC instruction completes |
|-------------------------|--------------------------------|--|--|---|
| 0x0 | SYNC or SYNC(0) | Loads, Stores | Loads, Stores | Loads, Stores |
| 0x2 | SYNC(2) Intervention Sync | Load,Stores | Loads, Stores | Loads, Stores |
| 0x3 | SYNC(3) Memory Sync | Load,Stores | Loads, Stores | Loads, Stores |
| 0x4 | SYNC_WMB or SYNC(4) | Stores | Stores | |
| 0x10 | SYNC_MB or SYNC(16) | Loads, Stores | Loads, Stores | |
| 0x11 | SYNC_ACQUIRE or SYNC(17) | Loads | Loads, Stores | |
| 0x12 | SYNC_RELEASE or SYNC(18) | Loads, Stores | Stores | |
| 0x13 | SYNC_RMB or SYNC(19) | Loads | Loads | |
| 0x1,0x5-0xF,0x14 - 0x1F | RESERVED | | | |

Restrictions:

None

Operation:

`SyncOperation(stype)`

Exceptions:

None

Software written to use a SYNC instruction with a non-zero stype value, expecting one type of barrier behavior, should only be run on hardware that actually implements the expected barrier behavior for that non-zero stype value or on hardware which implements a superset of the behavior expected by the software for that stype value. If the hardware does not perform the barrier behavior expected by the software, the system may fail.

processorprocessor

| | | | | | | | |
|----------------|---------|------------------------------|----|--|---|----------------|---|
| 31 | 26 | 25 | 24 | | 6 | 5 | 0 |
| COP0 010000 | CO 1 | 0 000 0000 0000 0000 0000 | | | | TLBR 000001 | |
| 6 | 1 | 19 | | | | 6 | |

Format: TLBR**MIPS32****Purpose:** Read Indexed TLB Entry

To read an entry from the TLB.

Description:

The *EntryHi*, *EntryLo0*, *EntryLo1*, and *PageMask* registers are loaded with the contents of the TLB entry pointed to by the *Index* register. In Release 1 of the Architecture, it is implementation dependent whether multiple TLB matches are detected on a TLBR. However, implementations are strongly encouraged to report multiple TLB matches only on a TLB write. In Release 2 of the Architecture, multiple TLB matches may only be reported on a TLB write. Note that the value written to the *EntryHi*, *EntryLo0*, and *EntryLo1* registers may be different from that originally written to the TLB via these registers in that:

- The value returned in the G bit in both the *EntryLo0* and *EntryLo1* registers comes from the single G bit in the TLB entry. Recall that this bit was set from the logical AND of the two G bits in *EntryLo0* and *EntryLo1* when the TLB was written.

Restrictions:

The operation is **UNDEFINED** if the contents of the Index register are greater than or equal to the number of TLB entries in the processor.

If access to Coprocessor 0 is not enabled, a Coprocessor Unusable Exception is signaled.

Operation:

```

i ← Index
if i > (TLBEntries - 1) then
    UNDEFINED
endif
PageMaskMask ← TLB[i]Mask
EntryHi ←
    TLB[i]VPN2 ||
    05 || TLB[i]ASID
EntryLo1 ← 02 ||
    TLB[i]PFN1 ||
    TLB[i]C1 || TLB[i]D1 || TLB[i]V1 || TLB[i]G
EntryLo0 ← 02 ||
    TLB[i]PFN0 ||
    TLB[i]C0 || TLB[i]D0 || TLB[i]V0 || TLB[i]G

```

Exceptions:

Coprocessor Unusable

| | | | | | | | |
|----------------|---------|------------------------------|----|--|---|-----------------|---|
| 31 | 26 | 25 | 24 | | 6 | 5 | 0 |
| COP0 010000 | CO 1 | 0 000 0000 0000 0000 0000 | | | | TLBWI 000010 | |
| 6 | 1 | 19 | | | | 6 | |

Format: TLBWI**MIPS32****Purpose:** Write Indexed TLB Entry

To write a TLB entry indexed by the *Index* register.

Description:

The TLB entry pointed to by the Index register is written from the contents of the *EntryHi*, *EntryLo0*, *EntryLo1*, and *PageMask* registers. It is implementation dependent whether multiple TLB matches are detected on a TLBWI. In such an instance, a Machine Check Exception is signaled. See [Section 4.4.1 “Hits, Misses, and Multiple Matches”](#) for the cases in which a 24K core will signal a Machine Check. The information written to the TLB entry may be different from that in the *EntryHi*, *EntryLo0*, and *EntryLo1* registers, in that:

- The single G bit in the TLB entry is set from the logical AND of the G bits in the *EntryLo0* and *EntryLo1* registers.

Restrictions:

The operation is **UNDEFINED** if the contents of the Index register are greater than or equal to the number of TLB entries in the processor.

If access to Coprocessor 0 is not enabled, a Coprocessor Unusable Exception is signaled.

Operation:

```

i ← Index
TLB[i]Mask ← PageMaskMask
TLB[i]VPN2 ← EntryHiVPN2
TLB[i]ASID ← EntryHiASID
TLB[i]G ← EntryLo1G and EntryLo0G
TLB[i]PFN1 ← EntryLo1PFN
TLB[i]C1 ← EntryLo1C
TLB[i]D1 ← EntryLo1D
TLB[i]V1 ← EntryLo1V
TLB[i]PFN0 ← EntryLo0PFN
TLB[i]C0 ← EntryLo0C
TLB[i]D0 ← EntryLo0D
TLB[i]V0 ← EntryLo0V

```

Exceptions:

Coprocessor Unusable

Machine Check

| | | | | | | | |
|----------------|---------|------------------------------|----|--|---|-----------------|---|
| 31 | 26 | 25 | 24 | | 6 | 5 | 0 |
| COP0 010000 | CO 1 | 0 000 0000 0000 0000 0000 | | | | TLBWR 000110 | |
| 6 | 1 | 19 | | | | 6 | |

Format: TLBWR**MIPS32****Purpose:** Write Random TLB Entry

To write a TLB entry indexed by the *Random* register.

Description:

The TLB entry pointed to by the *Random* register is written from the contents of the *EntryHi*, *EntryLo0*, *EntryLo1*, and *PageMask* registers. It is implementation dependent whether multiple TLB matches are detected on a TLBWR. In such an instance, a Machine Check Exception is signaled. See [Section 4.4.1 “Hits, Misses, and Multiple Matches”](#) for the cases in which a 24K core will signal a Machine Check. The information written to the TLB entry may be different from that in the *EntryHi*, *EntryLo0*, and *EntryLo1* registers, in that:

- The single G bit in the TLB entry is set from the logical AND of the G bits in the *EntryLo0* and *EntryLo1* registers.

Restrictions:

If access to Coprocessor 0 is not enabled, a Coprocessor Unusable Exception is signaled.

Operation:

```

i ← Random
TLB[i]Mask ← PageMaskMask
TLB[i]VPN2 ← EntryHiVPN2
TLB[i]ASID ← EntryHiASID
TLB[i]G ← EntryLo1G and EntryLo0G
TLB[i]PFN1 ← EntryLo1PFN
TLB[i]C1 ← EntryLo1C
TLB[i]D1 ← EntryLo1D
TLB[i]V1 ← EntryLo1V
TLB[i]PFN0 ← EntryLo0PFN
TLB[i]C0 ← EntryLo0C
TLB[i]D0 ← EntryLo0D
TLB[i]V0 ← EntryLo0V

```

Exceptions:

Coprocessor Unusable

Machine Check

| | | | | | | | |
|----------------|---------|-------------------------------|----|--|---|----------------|---|
| 31 | 26 | 25 | 24 | | 6 | 5 | 0 |
| COP0 010000 | CO 1 | Implementation-Dependent Code | | | | WAIT 100000 | |
| 6 | 1 | 19 | | | | 6 | |

Format: WAIT**MIPS32****Purpose:** Enter Standby Mode

Wait for Event

Description:

The WAIT instruction forces the core into low power mode. The pipeline is stalled and when all external requests are completed, the processor's main clock is stopped. The processor will restart when reset (*SI_Reset*) is signaled, or a non-masked interrupt is taken (*SI_NMI*, *SI_Int*, or *EJ_DINT*). Note that the core does not use the code field in this instruction.

If the pipeline restarts as the result of an enabled interrupt, that interrupt is taken between the WAIT instruction and the following instruction (EPC for the interrupt points at the instruction following the WAIT instruction). Note that it is also possible for an interrupt to be taken on the WAIT instruction itself (before the WAIT instruction has halted the pipeline). Software should be aware of this possibility and take appropriate actions to avoid returning to the WAIT if there is additional work to be done. This is the case for 'bottom half' interrupt processing that exists in Linux and other OSes. To facilitate this, the core implements a feature where the pipeline will be unfrozen by an interrupt even if Status_{IE}=0. The idle loop can thus disable interrupts prior to executing the WAIT and know that processing will resume after the WAIT when an interrupt is signaled. On a processor that does not support this feature, this sequence would prevent the core from waking up without a reset or NMI, so it should be verified that the feature is present. This core indicates that the feature is present by a value of 1 for Config7_{WII}

Restrictions:

The operation of the processor is **UNDEFINED** if a WAIT instruction is placed in the delay slot of a branch or a jump.

If access to Coprocessor 0 is not enabled, a Coprocessor Unusable Exception is signaled.

Operation:

```
I: Enter lower power mode
I+1:/* Potential interrupt taken here */
```

Exceptions:

Coprocessor Unusable Exception

MIPS16e™ Application-Specific Extension to the MIPS32® Instruction Set

This chapter describes the MIPS16e ASE as *implemented* in the 24K core. Refer to Volume IV-a of the *MIPS32® Architecture Reference Manual* [3] for a general description of the MIPS16e ASE and descriptions of the instructions.

This chapter covers the following topics:

- [Section 13.1 “Instruction Bit Encoding”](#)
- [Section 13.2 “Instruction Listing”](#)

13.1 Instruction Bit Encoding

[Table 13.2](#) through [Table 13.9](#) describe the encoding used for the MIPS16e ASE. [Table 13.1](#) describes the meaning of the symbols used in the tables.

Table 13.1 Symbols Used in the Instruction Encoding Tables

| Symbol | Meaning |
|---------------|--|
| * | Operation or field codes marked with this symbol are reserved for future use. Executing such an instruction cause a Reserved Instruction Exception. |
| δ | (Also <i>italic</i> field name.) Operation or field codes marked with this symbol denotes a field class. The instruction word must be further decoded by examining additional tables that show values for another instruction field. |
| β | Operation or field codes marked with this symbol represent a valid encoding for a higher-order MIPS ISA level. Executing such an instruction cause a Reserved Instruction Exception. |
| θ | Operation or field codes marked with this symbol are available to licensed MIPS partners. To avoid multiple conflicting instruction definitions, the partner must notify MIPS Technologies, Inc. when one of these encodings is used. If no instruction is encoded with this value, executing such an instruction must cause a Reserved Instruction Exception (<i>SPECIAL2</i> encodings or coprocessor instruction encodings for a coprocessor to which access is allowed) or a Coprocessor Unusable Exception (coprocessor instruction encodings for a coprocessor to which access is not allowed). |
| σ | Field codes marked with this symbol represent an EJTAG support instruction and implementation of this encoding is optional for each implementation. If the encoding is not implemented, executing such an instruction must cause a Reserved Instruction Exception. If the encoding is implemented, it must match the instruction encoding as shown in the table. |
| ε | Operation or field codes marked with this symbol are reserved for MIPS Application Specific Extensions. If the ASE is not implemented, executing such an instruction must cause a Reserved Instruction Exception. |
| ϕ | Operation or field codes marked with this symbol are obsolete and will be removed from a future revision of the MIPS64 ISA. Software should avoid using these operation or field codes. |

Table 13.2 MIPS16e Encoding of the Opcode Field

| opcode | | bits 13..11 | | | | | | | |
|-------------|----|----------------------|----------------------|-------------------|-----------------|--------------|-------------|-------------------|---------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 15..14 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | ADDIUSP ¹ | ADDIUPC ² | B | JAL(X) δ | BEQZ | BNEZ | SHIFT δ | β |
| 1 | 01 | RRI-A δ | ADDIU8 ³ | SLTI | SLTIU | I8 δ | LI | CMPI | β |
| 2 | 10 | LB | LH | LWSP ⁴ | LW | LBU | LHU | LWPC ⁵ | β |
| 3 | 11 | SB | SH | SWSP ⁶ | SW | RRR δ | RR δ | EXTEND δ | β |

1. The ADDIUSP opcode is used by the ADDIU rx, sp, immediate instruction
2. The ADDIUPC opcode is used by the ADDIU rx, pc, immediate instruction
3. The ADDIU8 opcode is used by the ADDIU rx, immediate instruction
4. The LWSP opcode is used by the LW rx, offset(sp) instruction
5. The LWPC opcode is used by the LW rx, offset(pc) instruction
6. The SWSP opcode is used by the SW rx, offset(sp) instruction

Table 13.3 MIPS16e JAL(X) Encoding of the x Field

| x | bit 26 | |
|---|--------|------|
| | 0 | 1 |
| | JAL | JALX |

Table 13.4 MIPS16e SHIFT Encoding of the f Field

| f | bits 1..0 | | | |
|---|-----------|---------|-----|-----|
| | 0 | 1 | 2 | 3 |
| | 00 | 01 | 10 | 11 |
| | SLL | β | SRL | SRA |

Table 13.5 MIPS16e RRI-A Encoding of the f Field

| f | bit 4 | |
|---|--------------------|---------|
| | 0 | 1 |
| | ADDIU ¹ | β |

1. The ADDIU function is used by the ADDIU ry, rx, immediate instruction

Table 13.6 MIPS16e I8 Encoding of the funct Field

| funct | bits 10..8 | | | | | | | |
|-------|------------|-------|---------------------|--------------------|---------------|---------------------|-----|---------------------|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| | BTEQZ | BTNEZ | SWRASP ¹ | ADJSP ² | SVRS δ | MOV32R ³ | * | MOVR32 ⁴ |

1. The SWRASP function is used by the SW ra, offset(sp) instruction
2. The ADJSP function is used by the ADDIU sp, immediate instruction
3. The MOV32R function is used by the MOVE r32, rz instruction
4. The MOVR32 function is used by the MOVE ry, r32 instruction

Table 13.7 MIPS16e RRR Encoding of the f Field

| f | bits 1..0 | | | |
|---|-----------|------|---------|------|
| | 0 | 1 | 2 | 3 |
| | 00 | 01 | 10 | 11 |
| | β | ADDU | β | SUBU |

Table 13.8 MIPS16e RR Encoding of the Funct Field

| funct | | bits 2..0 | | | | | | | |
|-----------|----|--------------------|---------------|------|---------|---------|---------|---------|---------|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| bits 4..3 | | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| 0 | 00 | $J(AL)R(C) \delta$ | SDBBP | SLT | SLTU | SLLV | BREAK | SRLV | SRAV |
| 1 | 01 | β | * | CMP | NEG | AND | OR | XOR | NOT |
| 2 | 10 | MFHI | $CNVT \delta$ | MFLO | β | β | * | β | β |
| 3 | 11 | MULT | MULTU | DIV | DIVU | β | β | β | β |

Table 13.9 MIPS16e I8 Encoding of the s Field when funct=SVRS

| s | bit 7 | |
|---|---------|------|
| | 0 | 1 |
| | RESTORE | SAVE |

Table 13.10 MIPS16e RR Encoding of the ry Field when funct=J(AL)R(C)

| ry | bits 7..5 | | | | | | | |
|----|-----------|-------|------|-----|--------|--------|-------|-----|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| | JR rx | JR ra | JALR | * | JRC rx | JRC ra | JALRC | * |

Table 13.11 MIPS16e RR Encoding of the ry Field when funct=CNVT

| ry | bits 7..5 | | | | | | | |
|----|-----------|-----|-----|-----|-----|-----|-----|-----|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
| | ZEB | ZEH | β | * | SEB | SEH | β | * |

13.2 Instruction Listing

Table 13.12 through 13.19 list the MIPS16e instruction set.

Table 13.12 MIPS16e Load and Store Instructions

| Mnemonic | Instruction | Extensible Instruction |
|----------|------------------------|------------------------|
| LB | Load Byte | Yes |
| LBU | Load Byte Unsigned | Yes |
| LH | Load Halfword | Yes |
| LHU | Load Halfword Unsigned | Yes |
| LW | Load Word | Yes |
| SB | Store Byte | Yes |
| SH | Store Halfword | Yes |
| SW | Store Word | Yes |

Table 13.13 MIPS16e Save and Restore Instructions

| Mnemonic | Instruction | Extensible Instruction |
|----------|--|------------------------|
| RESTORE | Restore Registers and Deallocate Stack Frame | Yes |
| SAVE | Save Registers and Setup Stack Frame | Yes |

Table 13.14 MIPS16e ALU Immediate Instructions

| Mnemonic | Instruction | Extensible Instruction |
|----------|-------------------------------------|------------------------|
| ADDIU | Add Immediate Unsigned | Yes |
| CMPI | Compare Immediate | Yes |
| LI | Load Immediate | Yes |
| SLTI | Set on Less Than Immediate | Yes |
| SLTIU | Set on Less Than Immediate Unsigned | Yes |

Table 13.15 MIPS16e Arithmetic Two or Three Operand Register Instructions

| Mnemonic | Instruction | Extensible Instruction |
|-----------------|---------------------------|-------------------------------|
| ADDU | Add Unsigned | No |
| AND | AND | No |
| CMP | Compare | No |
| MOVE | Move | No |
| NEG | Negate | No |
| NOT | Not | No |
| OR | OR | No |
| SEB | Sign-Extend Byte | No |
| SEH | Sign-Extend Halfword | No |
| SLT | Set on Less Than | No |
| SLTU | Set on Less Than Unsigned | No |
| SUBU | Subtract Unsigned | No |
| XOR | Exclusive OR | No |
| ZEB | Zero-Extend Byte | No |
| ZEH | Zero-Extend Halfword | No |

Table 13.16 MIPS16e Special Instructions

| Mnemonic | Instruction | Extensible Instruction |
|-----------------|---------------------------|-------------------------------|
| BREAK | Breakpoint | No |
| SDBBP | Software Debug Breakpoint | No |
| EXTEND | Extend | No |

Table 13.17 MIPS16e Multiply and Divide Instructions

| Mnemonic | Instruction | Extensible Instruction |
|-----------------|--------------------|-------------------------------|
| DIV | Divide | No |
| DIVU | Divide Unsigned | No |
| MFHI | Move From HI | No |
| MFLO | Move From LO | No |
| MULT | Multiply | No |
| MULTU | Multiply Unsigned | No |

Table 13.18 MIPS16e Jump and Branch Instructions

| Mnemonic | Instruction | Extensible Instruction |
|-----------------|--------------------------------|-------------------------------|
| B | Branch Unconditional | Yes |
| BEQZ | Branch on Equal to Zero | Yes |
| BNEZ | Branch on Not Equal to Zero | Yes |
| BTEQZ | Branch on T Equal to Zero | Yes |
| BTNEZ | Branch on T Not Equal to Zero | Yes |
| JAL | Jump and Link | No |
| JALR | Jump and Link Register | No |
| JALRC | Jump and Link Register Compact | No |
| JALX | Jump and Link Exchange | No |
| JR | Jump Register | No |
| JRC | Jump Register Compact | No |

Table 13.19 MIPS16e Shift Instructions

| Mnemonic | Instruction | Extensible Instruction |
|-----------------|---------------------------------|-------------------------------|
| SRA | Shift Right Arithmetic | Yes |
| SRAV | Shift Right Arithmetic Variable | No |
| SLL | Shift Left Logical | Yes |
| SLLV | Shift Left Logical Variable | No |
| SRL | Shift Right Logical | Yes |
| SRLV | Shift Right Logical Variable | No |

References

This appendix lists other documents available from MIPS Technologies, Inc. that are referenced elsewhere in this document. These documents may be included in the `$MIPS_HOME/$MIPS_CORE/doc` area of a typical 24K soft or hard core release, or in some cases may be available on the MIPS web site, <http://www.mips.com>.

1. MIPS32® Architecture For Programmers, Volume I: Introduction to the MIPS32® Architecture
MIPS document: MD0082
2. MIPS32® Architecture For Programmers, Volume II: The MIPS32® Instruction Set
MIPS document: MD0082
3. MIPS32® Architecture For Programmers, Volume IV-a: The MIPS16e™ Application-Specific Extension to the MIPS32® Architecture
MIPS document: MD00074
4. MIPS32® Architecture For Programmers, Volume IV-e: The MIPS® DSP Application-Specific Extension to the MIPS32® Architecture
MIPS document: MD00374
5. MIPS32® 24K® and 24KE™ Processor Core Family Integrator's Guide
MIPS document: MD00344
6. MIPS32® 24K® and 24KE™ Processor Core Family Implementor's Guide
MIPS document: MD00347
7. Programming the MIPS32® 24K® Processor Core Family
MIPS document: MD00355
8. CoreExtend® Instruction Integrator's Guide for MIPS32® Cores
MIPS document: MD00348
9. PDtrace™ Interface and Trace Control Block Specification
MIPS document: MD00439
10. Open Core Protocol Specification
Available from the OCP International Partnership at <http://www.ocpip.org>
11. EJTAG Specification
MIPS document: MD00047

Revision History

Change bars (vertical lines) in the margins of this document indicate significant changes in the document since its last release. Change bars are removed for changes that are more than one revision old.

This document may refer to Architecture specifications (for example, instruction set descriptions and EJTAG register definitions), and change bars in these sections indicate changes since the previous version of the relevant Architecture document.

| Revision | Date | Description |
|----------|--------------------|---|
| 0.90 | July 17, 2003 | <ul style="list-style-type: none"> Initial version. |
| 0.91 | July 31, 2003 | <ul style="list-style-type: none"> Updates based on early feedback |
| 0.92 | August 8, 2003 | <ul style="list-style-type: none"> Preliminary external release |
| 0.93 | August 22, 2003 | <ul style="list-style-type: none"> Added note on Cache Error handling to EBase description Added Status_{CEE} bit. Define writeability/reset state of ErrCtl_{PCO} bit Added MTHI/LO to MDU op latency, fixed MDU repeat rate table Removed DMTC1 and DMFC1 references from FPU chapter Updated PREF description to include special handling of streamed and retained types |
| 0.94 | September 15, 2003 | <ul style="list-style-type: none"> formatting changes to appendix, table of contents, list of figures, and list of tables minor clarification to Config_{MM} description. Changed Debug_{MCheckP} and Debug_{IBusEP} to reflect imprecise exceptions that the core can take. |
| 0.95 | September 30, 2003 | <ul style="list-style-type: none"> Added Config_{7AR} and Config_{7ES} fields |
| 0.96 | November 4, 2003 | <ul style="list-style-type: none"> Misc. cleanup |
| 0.97 | December 3, 2003 | <ul style="list-style-type: none"> Fix text to reflect 4I/2D as only EJTAG breakpoint option changed description of Config₇ fields Added WS=1 table to CACHE description update trademarks |
| 01.00 | December 10, 2003 | <ul style="list-style-type: none"> Updated EJTAG chapter - describe imprecise breakpoint handling, add 64b data compare for FP load/store |
| 01.01 | December 19, 2003 | <ul style="list-style-type: none"> Updated COP0 registers chapter - improved description for Errctl and TagLo. Also, made minor updates to the CACHE instruction description accordingly. |
| 1.02 | December 23, 2003 | <ul style="list-style-type: none"> Updated Table 2.7 Execution Hazards to reflect the actual instruction spacing |
| 1.03 | January 27, 2004 | <ul style="list-style-type: none"> Fixed config2 description - L2 cache is supported Add Config_{7.FPR} bit indicating FPU clock ratio Changed EB_SBlock to SI_SBlock in Config.BM description |

| Revision | Date | Description |
|----------|--------------------|--|
| 02.00 | March 5, 2004 | <ul style="list-style-type: none"> • Clarified possible of number of hardware breakpoints. • Added CEU exception type to table of Cause_{ExcCode} values. • Clarify special exception type values for EJTAG. • Removed TBD of fatal conditions in CacheErr • Redefined ErrCtl to reflect additional I\$ parity bits • Removed SI_ColdReset reference in WAIT description • Updated MDU latencies • Removed DataLo register for L2 cache • Update description of 64b data value register for EJTAG data value breaks • Change reset state of Config7_{ES} • Change priority of imprecise DDBL/DDBS breakpoints |
| 02.01 | May 28, 2004 | <ul style="list-style-type: none"> • Add Cache Error description to exception chapter • Fix Bus Error description in exception chapter • Clarified description of ErrCtl_{PE} field based on cache parity support • Add Machine Check Exception table to MMU Chapter |
| 02.02 | September 10, 2004 | <ul style="list-style-type: none"> • Review draft for MR1 release • Add details on coprocessor2 and scratchpad RAM interfaces |
| 03.00 | September 24, 2004 | <ul style="list-style-type: none"> • MR1 release |
| 03.01 | November 10, 2004 | <ul style="list-style-type: none"> • MIP16e pipe stages clarified |
| 3.02 | March 15, 2005 | <ul style="list-style-type: none"> • MIPS Trace capability described • Update hazard from TLBP |
| 3.03 | March 24, 2005 | <ul style="list-style-type: none"> • Updated the CacheErr register description |
| 3.04 | April 29, 2005 | <ul style="list-style-type: none"> • Added details on Instruction ScratchPad RAM |
| 3.05 | June 30, 2005 | <ul style="list-style-type: none"> • Added new performance counter events • Clarified handling of CACHE instruction to Data ScratchPad RAM • Added EJTAG PC Sampling capability and compliance to EJTAG specification version 3.1. • Updates to comply with PDtrace and TCB Specification version 4.1; added TCBCONTROL_{LC} register. |
| 3.06 | December 21, 2005 | <ul style="list-style-type: none"> • Removed use of undefined 'cache block' term from CACHE instruction description • Clarified which coprocessor0 registers were used by CACHE instructions • Remove description of non-way select or spram CACHE instructions when ErrCtl_{WST/SPR} bits are set • Update Config1 and TagLo descriptions to reflect 8KB cache option • Update description of debug control register to reflect PC Sampling • Added Config7.NBLSU |
| 3.07 | June 23, 2006 | <ul style="list-style-type: none"> • Removed duplicate write buffer full stall perfcoun event • Enabled support for TCBCONTROL_{B_{TW}SrcWidth} • Added exception vector address for Cache Error in Section 5.5, "Exception Vector Base Addresses when SI_UseExceptionBase equals 0" • Update description of Status_{RE} field. • Added descriptions for new registers SDataHi and SDataLo. • Added descriptions for CacheErr register for L2 cache errors. |

Revision History

| Revision | Date | Description |
|----------|-------------------|--|
| 3.08 | December 19, 2006 | <ul style="list-style-type: none"> Added ability to modify exception base when <code>Status_{BEV}</code> is 1 Added descriptions of perfcouter events Updated implementation-dependent instruction descriptions Updated description for L2 bypass bit in <code>Config2</code> Enhanced description for External SYNC indication in <code>Config7</code> |
| 3.10 | November 1, 2007 | <ul style="list-style-type: none"> Removed MT exception descriptions Fix <code>Status_{RE}</code> description Update document template to nB1.03 Added FE and SE bits to CP0 <code>ErrCtl</code> register Added CP0 <code>UserLocal</code> register with conditional access via RDHWR instruction. <code>Config3.ULRI</code> indicates presence of User-Local. Added hardware support to avoid virtual aliases in the Instruction Cache. Allow interrupt to unblock WAIT instruction even if <code>Status.IE</code> is disabled. |
| 3.11 | December 19, 2008 | <ul style="list-style-type: none"> Fixed position of <code>HWREna_{CCRes}</code> bit Remove <code>ErrCtl_{ITC}</code> since it is not present on this core Made performance counter event names more consistent Added Mode column to performance counter event table Added system specific performance counter events Clarified <code>IntCtl.IPPCI</code> description Removed self-referential notes for some instructions in the Core Instruction Set table. Added missing <code>DebugControlRegisterPCSe</code> bit as well as other DCR bits for unsupported debug features |