MIPS32™ Architecture For Programmers Volume III: The MIPS32™ Privileged Resource Architecture

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About This Book

The MIPS32™ Architecture For Programmers Volume III comes as a multi-volume set.

- Volume I describes conventions used throughout the document set, and provides an introduction to the MIPS32™ Architecture
- Volume II provides detailed descriptions of each instruction in the MIPS32™ instruction set
- Volume III describes the MIPS32™ Privileged Resource Architecture which defines and governs the behavior of the privileged resources included in a MIPS32™ processor implementation
- Volume IV-a describes the MIPS16™ Application-Specific Extension to the MIPS32™ Architecture
- Volume IV-b describes the MDMX™ Application-Specific Extension to the MIPS32™ Architecture and is not applicable to the MIPS32™ document set
- Volume IV-c describes the MIPS-3D™ Application-Specific Extension to the MIPS64™ Architecture and is not applicable to the MIPS32™ document set
- Volume IV-d describes the SmartMIPS™Application-Specific Extension to the MIPS32™ Architecture

1.1 Typographical Conventions

This section describes the use of *italic*, **bold** and `courier` fonts in this book.

1.1.1 Italic Text

- is used for *emphasis*
- is used for *bits*, *fields*, *registers*, that are important from a software perspective (for instance, address bits used by software, and programmable fields and registers), and various *floating point instruction formats*, such as *S*, *D*, and *PS*
- is used for the memory access types, such as *cached* and *uncached*

1.1.2 Bold Text

- represents a term that is being **defined**
- is used for **bits** and **fields** that are important from a hardware perspective (for instance, **register** bits, which are not programmable but accessible only to hardware)
- is used for ranges of numbers; the range is indicated by an ellipsis. For instance, **5..1** indicates numbers 5 through 1
- is used to emphasize **UNPREDICTABLE** and **UNDEFINED** behavior, as defined below.

1.1.3 Courier Text

`Courier` fixed-width font is used for text that is displayed on the screen, and for examples of code and instruction pseudocode.

1.2 UNPREDICTABLE and UNDEFINED

The terms **UNPREDICTABLE** and **UNDEFINED** are used throughout this book to describe the behavior of the processor in certain cases. **UNDEFINED** behavior or operations can occur only as the result of executing instructions in a privileged mode (i.e., in Kernel Mode or Debug Mode, or with the CP0 usable bit set in the Status register). Unprivileged software can never cause **UNDEFINED** behavior or operations. Conversely, both privileged and unprivileged software can cause **UNPREDICTABLE** results or operations.

1.2.1 UNPREDICTABLE

UNPREDICTABLE results may vary from processor implementation to implementation, instruction to instruction, or as a function of time on the same implementation or instruction. Software can never depend on results that are **UNPREDICTABLE**. **UNPREDICTABLE** operations may cause a result to be generated or not. If a result is generated, it is **UNPREDICTABLE**. **UNPREDICTABLE** operations may cause arbitrary exceptions.

UNPREDICTABLE results or operations have several implementation restrictions:

- Implementations of operations generating **UNPREDICTABLE** results must not depend on any data source (memory or internal state) which is inaccessible in the current processor mode
- **UNPREDICTABLE** operations must not read, write, or modify the contents of memory or internal state which is inaccessible in the current processor mode. For example, **UNPREDICTABLE** operations executed in user mode must not access memory or internal state that is only accessible in Kernel Mode or Debug Mode or in another process
- **UNPREDICTABLE** operations must not halt or hang the processor

1.2.2 UNDEFINED

UNDEFINED operations or behavior may vary from processor implementation to implementation, instruction to instruction, or as a function of time on the same implementation or instruction. **UNDEFINED** operations or behavior may vary from nothing to creating an environment in which execution can no longer continue. **UNDEFINED** operations or behavior may cause data loss.

UNDEFINED operations or behavior has one implementation restriction:

- **UNDEFINED** operations or behavior must not cause the processor to hang (that is, enter a state from which there is no exit other than powering down the processor). The assertion of any of the reset signals must restore the processor to an operational state

1.3 Special Symbols in Pseudocode Notation

In this book, algorithmic descriptions of an operation are described as pseudocode in a high-level language notation resembling Pascal. Special symbols used in the pseudocode notation are listed in Table 1-1.

Table 1-1 Symbols Used in Instruction Operation Statements

Symbol	Meaning
←	Assignment
=, ≠	Tests for equality and inequality
||	Bit string concatenation
x^y	A *y*-bit string formed by *y* copies of the single-bit value *x*
b#n	A constant value *n* in base *b*. For instance 10#100 represents the decimal value 100, 2#100 represents the binary value 100 (decimal 4), and 16#100 represents the hexadecimal value 100 (decimal 256). If the "b#" prefix is omitted, the default base is 10.
$x_{y..z}$	Selection of bits *y* through *z* of bit string *x*. Little-endian bit notation (rightmost bit is 0) is used. If *y* is less than *z*, this expression is an empty (zero length) bit string.
+, −	2's complement or floating point arithmetic: addition, subtraction
*, ×	2's complement or floating point multiplication (both used for either)
div	2's complement integer division
mod	2's complement modulo
/	Floating point division
<	2's complement less-than comparison
>	2's complement greater-than comparison
≤	2's complement less-than or equal comparison
≥	2's complement greater-than or equal comparison
nor	Bitwise logical NOR
xor	Bitwise logical XOR
and	Bitwise logical AND
or	Bitwise logical OR
GPRLEN	The length in bits (32 or 64) of the CPU general-purpose registers
GPR[x]	CPU general-purpose register *x*. The content of *GPR[0]* is always zero.
FPR[x]	Floating Point operand register *x*
FCC[CC]	Floating Point condition code CC. *FCC[0]* has the same value as *COC[1]*.
FPR[x]	Floating Point (Coprocessor unit 1), general register *x*
CPR[z,x,s]	Coprocessor unit *z*, general register *x*, select *s*
CCR[z,x]	Coprocessor unit *z*, control register *x*
COC[z]	Coprocessor unit *z* condition signal
Xlat[x]	Translation of the MIPS16 GPR number *x* into the corresponding 32-bit GPR number
BigEndianMem	Endian mode as configured at chip reset (0 →Little-Endian, 1 → Big-Endian). Specifies the endianness of the memory interface (see LoadMemory and StoreMemory pseudocode function descriptions), and the endianness of Kernel and Supervisor mode execution.

Table 1-1 Symbols Used in Instruction Operation Statements

Symbol	Meaning
BigEndianCPU	The endianness for load and store instructions (0 → Little-Endian, 1 → Big-Endian). In User mode, this endianness may be switched by setting the *RE* bit in the *Status* register. Thus, BigEndianCPU may be computed as (BigEndianMem XOR ReverseEndian).
ReverseEndian	Signal to reverse the endianness of load and store instructions. This feature is available in User mode only, and is implemented by setting the *RE* bit of the *Status* register. Thus, ReverseEndian may be computed as (SR_{RE} and User mode).
LLbit	Bit of **virtual** state used to specify operation for instructions that provide atomic read-modify-write. *LLbit* is set when a linked load occurs; it is tested and cleared by the conditional store. It is cleared, during other CPU operation, when a store to the location would no longer be atomic. In particular, it is cleared by exception return instructions.
I:, **I+n**:, **I-n**:	This occurs as a prefix to *Operation* description lines and functions as a label. It indicates the instruction time during which the pseudocode appears to "execute." Unless otherwise indicated, all effects of the current instruction appear to occur during the instruction time of the current instruction. No label is equivalent to a time label of **I**. Sometimes effects of an instruction appear to occur either earlier or later — that is, during the instruction time of another instruction. When this happens, the instruction operation is written in sections labeled with the instruction time, relative to the current instruction **I**, in which the effect of that pseudocode appears to occur. For example, an instruction may have a result that is not available until after the next instruction. Such an instruction has the portion of the instruction operation description that writes the result register in a section labeled **I+1**. The effect of pseudocode statements for the current instruction labelled **I+1** appears to occur "at the same time" as the effect of pseudocode statements labeled **I** for the following instruction. Within one pseudocode sequence, the effects of the statements take place in order. However, between sequences of statements for different instructions that occur "at the same time," there is no defined order. Programs must not depend on a particular order of evaluation between such sections.
PC	The *Program Counter* value. During the instruction time of an instruction, this is the address of the instruction word. The address of the instruction that occurs during the next instruction time is determined by assigning a value to *PC* during an instruction time. If no value is assigned to *PC* during an instruction time by any pseudocode statement, it is automatically incremented by either 2 (in the case of a 16-bit MIPS16 instruction) or 4 before the next instruction time. A taken branch assigns the target address to the *PC* during the instruction time of the instruction in the branch delay slot.
PABITS	The number of physical address bits implemented is represented by the symbol PABITS. As such, if 36 physical address bits were implemented, the size of the physical address space would be $2^{PABITS} = 2^{36}$ bytes.
FP32RegistersMode	Indicates whether the FPU has 32-bit or 64-bit floating point registers (FPRs). In MIPS32, the FPU has 32 32-bit FPRs in which 64-bit data types are stored in even-odd pairs of FPRs. In MIPS64, the FPU has 32 64-bit FPRs in which 64-bit data types are stored in any FPR. In MIPS32 implementations, **FP32RegistersMode** is always a 0. MIPS64 implementations have a compatibility mode in which the processor references the FPRs as if it were a MIPS32 implementation. In such a case **FP32RegisterMode** is computed from the FR bit in the *Status* register. If this bit is a 0, the processor operates as if it had 32 32-bit FPRs. If this bit is a 1, the processor operates with 32 64-bit FPRs. The value of **FP32RegistersMode** is computed from the FR bit in the *Status* register.
InstructionInBranchDelaySlot	Indicates whether the instruction at the Program Counter address was executed in the delay slot of a branch or jump. This condition reflects the *dynamic* state of the instruction, not the *static* state. That is, the value is false if a branch or jump occurs to an instruction whose PC immediately follows a branch or jump, but which is not executed in the delay slot of a branch or jump.
SignalException(exception, argument)	Causes an exception to be signaled, using the exception parameter as the type of exception and the argument parameter as an exception-specific argument). Control does not return from this pseudocode function - the exception is signaled at the point of the call.

1.4 For More Information

Various MIPS RISC processor manuals and additional information about MIPS products can be found at the MIPS URL:

http://www.mips.com

Comments or questions on the MIPS32™ Architecture or this document should be directed to

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The MIPS32 Privileged Resource Architecture

2.1 Introduction

The MIPS32 Privileged Resource Architecture (PRA) is a set of environments and capabilities on which the Instruction Set Architecture operates. The effects of some components of the PRA are user-visible, for instance, the virtual memory layout. Many other components are visible only to the operating system kernel and to systems programmers. The PRA provides the mechanisms necessary to manage the resources of the CPU: virtual memory, caches, exceptions and user contexts. This chapter describes these mechanisms.

2.2 The MIPS Coprocessor Model

The MIPS ISA provides for up to 4 coprocessors. A coprocessor extends the functionality of the MIPS ISA, while sharing the instruction fetch and execution control logic of the CPU. Some coprocessors, such as the system coprocessor and the floating point unit are standard parts of the ISA, and are specified as such in the architecture documents. Coprocessors are generally optional, with one exception: CP0, the system coprocessor, is required. CP0 is the ISA interface to the Privileged Resource Architecture and provides full control of the processor state and modes.

2.2.1 CP0 - The System Coprocessor

CP0 provides an abstraction of the functions necessary to support an operating system: exception handling, memory management, scheduling, and control of critical resources. The interface to CP0 is through various instructions encoded with the *COP0* opcode, including the ability to move data to and from the CP0 registers, and specific functions that modify CP0 state. The CP0 registers and the interaction with them make up much of the Privileged Resource Architecture.

2.2.2 CP0 Registers

The CP0 registers provide the interface between the ISA and the PRA. The CP0 registers are described in Chapter 6.

MIPS32 Operating Modes

The MIPS32 PRA requires two operating mode: User Mode and Kernel Mode. When operating in User Mode, the programmer has access to the CPU and FPU registers that are provided by the ISA and to a flat, uniform virtual memory address space. When operating in Kernel Mode, the system programmer has access to the full capabilities of the processor, including the ability to change virtual memory mapping, control the system environment, and context switch between processes.

In addition, the MIPS32 PRA supports the implementation of two additional modes: Supervisor Mode and EJTAG Debug Mode. Refer to the EJTAG specification for a description of Debug Mode.

3.1 Debug Mode

For processors that implement EJTAG, 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.

3.2 Kernel Mode

The processor is operating in Kernel Mode when the DM bit in the *Debug* register is a zero (if the processor implements Debug Mode), 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.

3.3 Supervisor Mode

The processor is operating in Supervisor Mode (if that optional mode is implemented by the processor) when all of the following conditions are true:

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

3.4 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 (if the processor implements Debug Mode)

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

Virtual Memory

4.1 Terminology

4.1.1 Address Space

An *Address Space* is the range of all possible addresses that can be generated. There is one 32-bit Address Space in the MIPS32 Architecture.

4.1.2 Segment and Segment Size

A *Segment* is a defined subset of an Address Space that has self-consistent reference and access behavior. Segments are either 2^{29} or 2^{31} bytes in size, depending on the specific Segment.

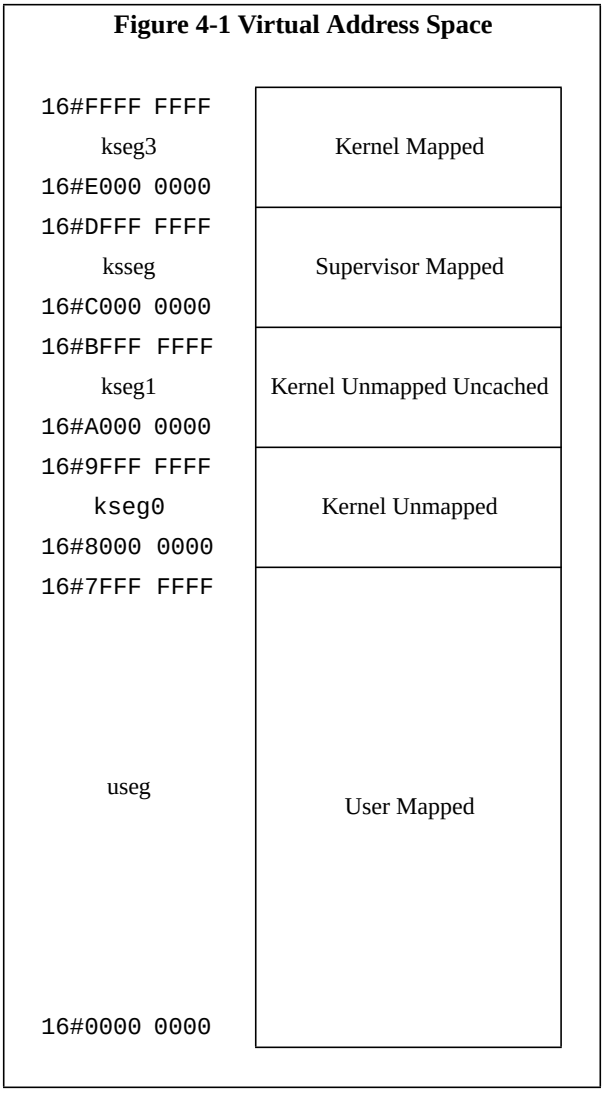
4.1.3 Physical Address Size (PABITS)

The number of physical address bits implemented is represented by the symbol *PABITS*. As such, if 36 physical address bits were implemented, the size of the physical address space would be $2^{PABITS} = 2^{36}$ bytes.

4.2 Virtual Address Spaces

The MIPS32 virtual address space is divided into five segments as shown in Figure 4-1.

Figure 4-1 Virtual Address Space



Each Segment of an Address Space is classified as “Mapped” or “Unmapped”. A “Mapped” address is one that is translated through the TLB or other address translation unit. An “Unmapped” address is one which is not translated through the TLB and which provides a window into the lowest portion of the physical address space, starting at physical address zero, and with a size corresponding to the size of the unmapped Segment.

Additionally, the kseg1 Segment is classified as “Uncached”. References to this Segment bypass all levels of the cache hierarchy and allow direct access to memory without any interference from the caches.

Table 4-1 lists the same information in tabular form.

Table 4-1 Virtual Memory Address Spaces

$VA_{31..29}$	Segment Name(s)	Address Range	Associated with Mode	Reference Legal from Mode(s)	Actual Segment Size
2#111	kseg3	16#FFFF FFFF through 16#E000 0000	Kernel	Kernel	2^{29} bytes

Table 4-1 Virtual Memory Address Spaces

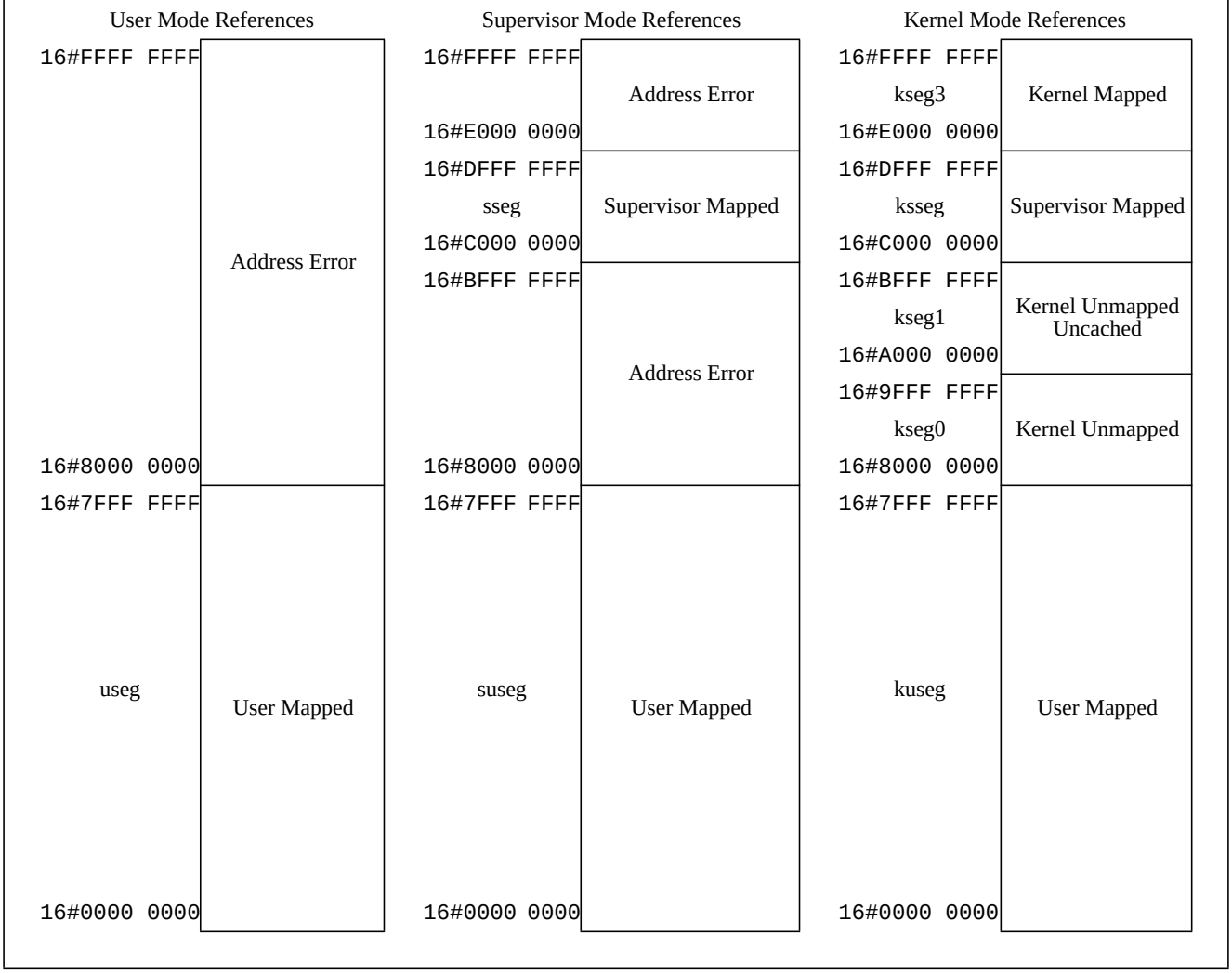
$VA_{31..29}$	Segment Name(s)	Address Range	Associated with Mode	Reference Legal from Mode(s)	Actual Segment Size
2#110	sseg ksseg	16#DFFF FFFF through 16#C000 0000	Supervisor	Supervisor Kernel	2^{29} bytes
2#101	kseg1	16#BFFF FFFF through 16#A000 0000	Kernel	Kernel	2^{29} bytes
2#100	kseg0	16#9FFF FFFF through 16#8000 0000	Kernel	Kernel	2^{29} bytes
2#0xx	useg suseg kuseg	16#7FFF FFFF through 16#0000 0000	User	User Supervisor Kernel	2^{31} bytes

Each Segment of an Address Space is associated with one of the three processor operating modes (User, Supervisor, or Kernel). A Segment that is associated with a particular mode is accessible if the processor is running in that or a more privileged mode. For example, a Segment associated with User Mode is accessible when the processor is running in User, Supervisor, or Kernel Modes. A Segment is not accessible if the processor is running in a less privileged mode than that associated with the Segment. For example, a Segment associated with Supervisor Mode is not accessible when the processor is running in User Mode and such a reference results in an Address Error Exception. The “Reference Legal from Mode(s)” column in Table 4-2 lists the modes from which each Segment may be legally referenced.

If a Segment has more than one name, each name denotes the mode from which the Segment is referenced. For example, the Segment name “useg” denotes a reference from user mode, while the Segment name “kuseg” denotes a reference to the same Segment from kernel mode.

Figure 4-2 shows the Address Space as seen when the processor is operating in each of the operating modes.

Figure 4-2 References as a Function of Operating Mode



4.3 Compliance

A MIPS32 compliant processor must implement the following Segments:

- useg/kuseg
- kseg0
- kseg1

In addition, a MIPS32 compliant processor using the TLB-based address translation mechanism must also implement the kseg3 Segment.

4.4 Access Control as a Function of Address and Operating Mode

Table 4-2 enumerates the action taken by the processor for each section of the 32-bit Address Space as a function of the operating mode of the processor. The selection of TLB Refill vector and other special-cased behavior is also listed for each reference.

Table 4-2 Address Space Access as a Function of Operating Mode

Virtual Address Range	Segment Name(s)	Action when Referenced from Operating Mode		
		User Mode	Supervisor Mode	Kernel Mode
16#FFFF FFFF through 16#E000 0000	kseg3	Address Error	Address Error	Mapped See 4.7 on page 16 for special behavior when $Debug_{DM}$ = 1
16#DFFF FFFF through 16#C000 0000	sseg ksseg	Address Error	Mapped	Mapped
16#BFFF FFFF through 16#A000 0000	kseg1	Address Error	Address Error	Unmapped, Uncached See Section 4.5 on page 15
16#9FFF FFFF through 16#8000 0000	kseg0	Address Error	Address Error	Unmapped See Section 4.5 on page 15
16#7FFF FFFF through 16#0000 0000	useg suseg kuseg	Mapped	Mapped	Unmapped if $Status_{ERL}$=1 See Section 4.6 on page 16 Mapped if $Status_{ERL}$=0

4.5 Address Translation and Cache Coherency Attributes for the kseg0 and kseg1 Segments

The kseg0 and kseg1 Unmapped Segments provide a window into the least significant 2^{29} bytes of physical memory, and, as such, are not translated using the TLB or other address translation unit. The cache coherency attribute of the kseg0 Segment is supplied by the K0 field of the CP0 *Config* register. The cache coherency attribute for the kseg1 Segment is always Uncached. Table 4-3 describes how this transformation is done, and the source of the cache coherency attributes for each Segment.

Table 4-3 Address Translation and Cache Coherency Attributes for the kseg0 and kseg1 Segments

Segment Name	Virtual Address Range	Generates Physical Address	Cache Attribute
kseg1	16#BFFF FFFF through 16#A000 0000	16#1FFF FFFF through 16#0000 0000	Uncached
kseg0	16#9FFF FFFF through 16#8000 0000	16#1FFF FFFF through 16#0000 0000	From K0 field of *Config* Register

4.6 Address Translation for the kuseg Segment when $Status_{ERL} = 1$

To provide support for the cache error handler, the kuseg Segment becomes an unmapped, uncached Segment, similar to the kseg1 Segment, if the ERL bit is set in the *Status* register. This allows the cache error exception code to operate uncached using GPR R0 as a base register to save other GPRs before use.

4.7 Special Behavior for the kseg3 Segment when $Debug_{DM} = 1$

If EJTAG is implemented on the processor, the EJTAG block must treat the virtual address range 16#FF20 0000 through 16#FF3F FFFF, inclusive, as a special memory-mapped region in Debug Mode. A MIPS32 compliant implementation that also implements EJTAG must:

- explicitly range check the address range as given and not assume that the entire region between 16#FF20 0000 and 16#FFFF FFFF is included in the special memory-mapped region.
- not enable the special EJTAG mapping for this region in any mode other than in EJTAG Debug mode.

Even in Debug mode, normal memory rules may apply in some cases. Refer to the EJTAG specification for details on this mapping.

4.8 TLB-Based Virtual Address Translation

This section describes the TLB-based virtual address translation mechanism. Note that sufficient TLB entries must be implemented to avoid a TLB exception loop on load and store instructions.

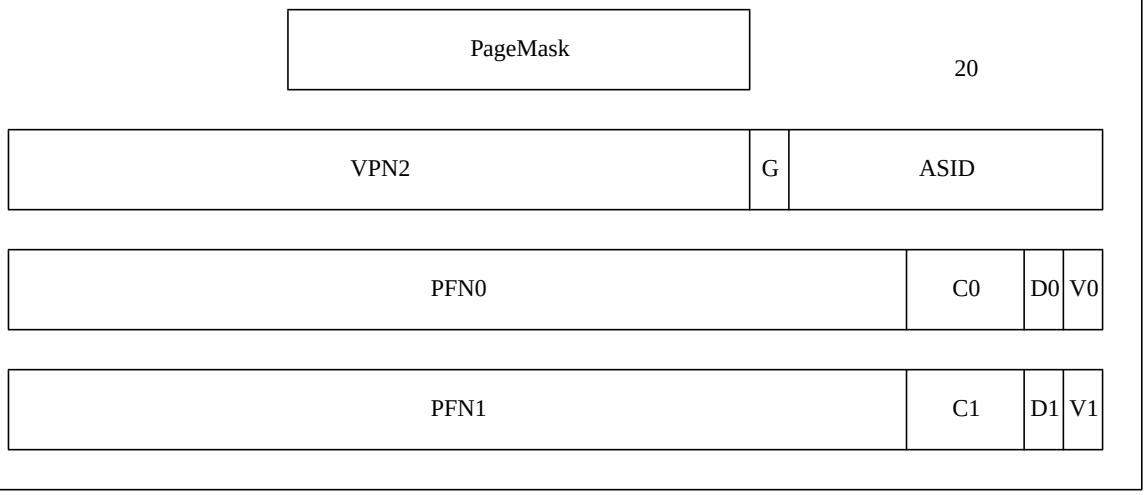
4.8.1 Address Space Identifiers (ASID)

The TLB-based translation mechanism supports Address Space Identifiers to uniquely identify the same virtual address across different processes. The operating system assigns ASIDs to each process and the TLB keeps track of the ASID when doing address translation. In certain circumstances, the operating system may wish to associate the same virtual address with all processes. To address this need, the TLB includes a global (G) bit which over-rides the ASID comparison during translation.

4.8.2 TLB Organization

The TLB is a fully-associative structure which is used to translate virtual addresses. Each entry contains two logical components: a comparison section and a physical translation section. The comparison section includes the virtual page number (VPN2) (actually, the virtual page number/2 since each entry maps two physical pages) of the entry, the ASID, the G(lobal) bit and a recommended mask field which provides the ability to map different page sizes with a single entry. The physical translation section contains a pair of entries, each of which contains the physical page frame number (PFN), a valid (V) bit, a dirty (D) bit, and a cache coherency field (C), whose valid encodings are given in Table 6-6 on page 44. There are two entries in the translation section for each TLB entry because each TLB entry maps an aligned pair of virtual pages and the pair of physical translation entries corresponds to the even and odd pages of the pair. Figure 4-3 shows the logical arrangement of a TLB entry.

Figure 4-3 Contents of a TLB Entry



The fields of the TLB entry correspond exactly to the fields in the CP0 *PageMask*, *EntryHi*, *EntryLo0* and *EntryLo1* registers. The even page entries in the TLB (e.g., PFN0) come from *EntryLo0*. Similarly, odd page entries come from *EntryLo1*.

4.8.3 Address Translation

When an address translation is requested, the virtual page number and the current process ASID are presented to the TLB. All entries are checked simultaneously for a match, which occurs when all of the following conditions are true:

- The current process ASID (as obtained from the *EntryHi* register) matches the ASID field in the TLB entry, or the G bit is set in the TLB entry.
- The appropriate bits of the virtual page number match the corresponding bits of the VPN2 field stored within the TLB entry. The “appropriate” number of bits is determined by the PageMask field in each entry by ignoring each bit in the virtual page number and the TLB VPN2 field corresponding to those bits that are set in the PageMask field. This allows each entry of the TLB to support a different page size, as determined by the PageMask register at the time that the TLB entry was written. If the recommended PageMask register is not implemented, the TLB operation is as if the PageMask register was written with a zero, resulting in a minimum 4096-byte page size.

If a TLB entry matches the address and ASID presented, the corresponding PFN, C, V, and D bits are read from the translation section of the TLB entry. Which of the two PFN entries is read is a function of the virtual address bit immediately to the right of the section masked with the PageMask entry.

The valid and dirty bits determine the final success of the translation. If the valid bit is off, the entry is not valid and a TLB Invalid exception is raised. If the dirty bit is off and the reference was a store, a TLB Modified exception is raised.

If there is an address match with a valid entry and no dirty exception, the PFN and the cache coherency bits are appended to the offset-within-page bits of the address to form the final physical address with attributes.

The TLB lookup process can be described as follows:

```
found ← 0
for i in 0...TLBEntries-1
   if ((TLB[i]VPN2 and not (TLB[i]Mask)) = (va31..13 and not (TLB[i]Mask))) and
      (TLB[i]G or (TLB[i]ASID = EntryHiASID)) then
      # EvenOddBit selects between even and odd halves of the TLB as a function of
      # the page size in the matching TLB entry
      case TLB[i]Mask
         2#0000000000000000: EvenOddBit ← 12
         2#0000000000000011: EvenOddBit ← 14
         2#0000000000001111: EvenOddBit ← 16
         2#0000000000111111: EvenOddBit ← 18
         2#0000000011111111: EvenOddBit ← 20
         2#0000001111111111: EvenOddBit ← 22
         2#0000111111111111: EvenOddBit ← 24
         2#0011111111111111: EvenOddBit ← 26
         2#1111111111111111: EvenOddBit ← 28
         otherwise:   UNDEFINED
      endcase
      if vaEvenOddBit = 0 then
         pfn ← TLB[i]PFN0
         v ← TLB[i]V0
         c ← TLB[i]C0
         d ← TLB[i]D0
      else
         pfn ← TLB[i]PFN1
         v ← TLB[i]V1
         c ← TLB[i]C1
         d ← TLB[i]D1
      endif
      if v = 0 then
         SignalException(TLBInvalid, reftype)
      endif
      if (d = 0) and (reftype = store) then
         SignalException(TLBModified)
      endif
      # pfnPABITS-1-12..0 corresponds to paPABITS-1..12
      pa ← pfnPABITS-1-12..EvenOddBit-12 || vaEvenOddBit-1..0
      found ← 1
      break
   endif
endfor
if found = 0 then
   SignalException(TLBMiss, reftype)
endif
```

Table 4-4 demonstrates how the physical address is generated as a function of the page size of the TLB entry that matches the virtual address. The “Even/Odd Select” column of Table 4-4 indicates which virtual address bit is used to select between the even (EntryLo0) or odd (EntryLo1) entry in the matching TLB entry. The “PA generated from” column specifies how the physical address is generated from the selected PFN and the offset-in-page bits in the virtual

address. In this column, PFN is the physical page number as loaded into the TLB from the EntryLo0 or EntryLo1 registers, and has the bit range $PFN_{PABITS\text{-}1\text{-}12..0}$, corresponding to $PA_{PABITS\text{-}1..12}$.

Table 4-4 Physical Address Generation

Page Size	Even/Odd Select	PA generated from
4K Bytes	VA_{12}	$PFN_{PABITS\text{-}1\text{-}12..0} \| VA_{11..0}$
16K Bytes	VA_{14}	$PFN_{PABITS\text{-}1\text{-}12..2} \| VA_{13..0}$
64K Bytes	VA_{16}	$PFN_{PABITS\text{-}1\text{-}12..4} \| VA15..0$
256K Bytes	VA_{18}	$PFN_{PABITS\text{-}1\text{-}12..6} \| VA_{17..0}$
1M Bytes	VA_{20}	$PFN_{PABITS\text{-}1\text{-}12..8} \| VA_{19..0}$
4M Bytes	VA_{22}	$PFN_{PABITS\text{-}1\text{-}12..10} \| VA_{21..0}$
16M Bytes	VA_{24}	$PFN_{PABITS\text{-}1\text{-}12..12} \| VA_{23..0}$
64MBytes	VA_{26}	$PFN_{PABITS\text{-}1\text{-}12..14} \| VA_{25..0}$
256MBytes	VA_{28}	$PFN_{PABITS\text{-}1\text{-}12..16} \| VA_{27..0}$

Interrupts and Exceptions

5.1 Interrupts

The processor supports eight interrupt requests, broken down into four categories:

- Software interrupts - Two software interrupt requests are made via software writes to bits IP0 and IP1 of the *Cause* register.
- Hardware interrupts - Up to six hardware interrupt requests numbered 0 through 5 are made via implementation-dependent external requests to the processor.
- Timer interrupt - A timer interrupt is raised when the *Count* and *Compare* registers reach the same value.
- Performance counter interrupt - A performance counter interrupt is raised when the most significant bit of the counter is a one, and the interrupt is enabled by the IE bit in the performance counter control register.

Timer interrupts, performance counter interrupts, and hardware interrupt 5 are combined in an implementation dependent way to create the ultimate hardware interrupt 5.

The current interrupt requests are visible via the IP field in the *Cause* register on any read of that register (not just after an interrupt exception has occurred). The mapping of *Cause* register bits to the various interrupt requests is shown in Table 5-1.

Table 5-1 Mapping of Interrupts to the *Cause* and *Status* Registers

		***Cause* Register Bit**		***Status* Register Bit**	
Interrupt Type	**Interrupt Number**	**Number**	**Name**	**Number**	**Name**
Software Interrupt	0	8	IP0	8	IM0
	1	9	IP1	9	IM1
Hardware Interrupt	0	10	IP2	10	IM2
	1	11	IP3	11	IM3
	2	12	IP4	12	IM4
	3	13	IP5	13	IM5
	4	14	IP6	14	IM6
Hardware Interrupt, Timer Interrupt, or Performance Counter Interrupt	5	15	IP7	15	IM7

For each bit of the IP field in the *Cause* register there is a corresponding bit in the IM field in the *Status* register. An interrupt is only taken when all of the following are true:

- An interrupt request bit is a one in the IP field of the *Cause* register.
- The corresponding mask bit is a one in the IM field of the *Status* register. The mapping of bits is shown in Table 5-1.
- The IE bit in the *Status* register is a one.
- The DM bit in the *Debug* register is a zero (for processors implementing EJTAG)

- The EXL and ERL bits in the *Status* register are both zero.

Logically, the IP field of the *Cause* register is bit-wise ANDed with the IM field of the *Status* register, the eight resultant bits are ORed together and that value is ANDed with the IE bit of the *Status* register. The final interrupt request is then asserted only if both the EXL and ERL bits in the *Status* register are zero, and the DM bit in the *Debug* register is zero, corresponding to a non-exception, non-error, non-debug processing mode, respectively.

5.2 Exceptions

Normal execution of instructions may be interrupted when an exception occurs. Such events can be generated as a by-product of instruction execution (e.g., an integer overflow caused by an add instruction or a TLB miss caused by a load instruction), or by an event not directly related to instruction execution (e.g., an external interrupt). When an exception occurs, the processor stops processing instructions, saves sufficient state to resume the interrupted instruction stream, enters Kernel Mode, and starts a software exception handler. The saved state and the address of the software exception handler are a function of both the type of exception, and the current state of the processor.

5.2.1 Exception Vector Locations

The Reset, Soft Reset, and NMI exceptions are always vectored to location `16#BFC0 0000`. EJTAG Debug exceptions are vectored to location `16#BFC0 0480` or to location `16#FF20 0200` if the ProbEn bit is zero or one, respectively, in the EJTAG_Control_register. Addresses for all other exceptions are a combination of a vector offset and a base address. Table 5-2 gives the base address as a function of the exception and whether the BEV bit is set in the *Status* register. Table 5-3 gives the offsets from the base address as a function of the exception. Note that the IV bit in the CP0 *Cause* register causes Interrupts to use a dedicated exception vector offset, rather than the general exception vector. Table 5-4 combines these two tables into one that contains all possible vector addresses as a function of the state that can affect the vector selection.

Table 5-2 Exception Vector Base Addresses

Exception	$Status_{BEV}$	
	0	**1**
Reset, Soft 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	`16#A000 0000`	`16#BFC0 0200`
Other	`16#8000 0000`	`16#BFC0 0200`

Table 5-3 Exception Vector Offsets

Exception	Vector Offset
TLB Refill, EXL = 0	`16#000`
Cache error	`16#100`
General Exception	`16#180`
Interrupt, $Cause_{IV}$ = 1	`16#200`
Reset, Soft Reset, NMI	None (Uses Reset Base Address)

Table 5-4 Exception Vectors

Exception	$Status_{BEV}$	$Status_{EXL}$	$Cause_{IV}$	EJTAG ProbEn	Vector
Reset, Soft Reset, NMI	x	x	x	x	16#BFC0 0000
EJTAG Debug	x	x	x	0	16#BFC0 0480
EJTAG Debug	x	x	x	1	16#FF20 0200
TLB Refill	0	0	x	x	16#8000 0000
TLB Refill	0	1	x	x	16#8000 0180
TLB Refill	1	0	x	x	16#BFC0 0200
TLB Refill	1	1	x	x	16#BFC0 0380
Cache Error	0	x	x	x	16#A000 0100
Cache Error	1	x	x	x	16#BFC0 0300
Interrupt	0	0	0	x	16#8000 0180
Interrupt	0	0	1	x	16#8000 0200
Interrupt	1	0	0	x	16#BFC0 0380
Interrupt	1	0	1	x	16#BFC0 0400
All others	0	x	x	x	16#8000 0180
All others	1	x	x	x	16#BFC0 0380
‘x’ denotes don’t care					

5.2.2 General Exception Processing

With the exception of Reset, Soft Reset, and NMI 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 6-16 on page 58). 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 5-5 shows the value stored in each of the CP0 PC registers, including *EPC*.

  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.

Table 5-5 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)
Yes	No	Upper 31 bits of the address of the instruction, combined with the *ISA Mode* bit

Table 5-5 Value Stored in EPC, ErrorEPC, or DEPC on an Exception

MIPS16 Implemented?	In Branch/Jump Delay Slot?	Value stored in EPC/ErrorEPC/DEPC
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 *ISA Mode* 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 Status_EXL = 0
   if InstructionInBranchDelaySlot then
      EPC ← restartPC # PC of branch/jump
      Cause_BD ← 1
   else
      EPC ← restartPC # PC of instruction
      Cause_BD ← 0
   endif
   if ExceptionType = TLBRefill then
      vectorOffset ← 16#000
   elseif (ExceptionType = Interrupt) and
      (Cause_IV = 1) then
      vectorOffset ← 16#200
   else
      vectorOffset ← 16#180
   endif
else
   vectorOffset ← 16#180
endif
Cause_CE ← FaultingCoprocessorNumber
Cause_ExcCode ← ExceptionType
Status_EXL ← 1
if Status_BEV = 1 then
   PC ← 16#BFC0 0200 + vectorOffset
else
   PC ← 16#8000 0000 + vectorOffset
endif
```

5.2.3 EJTAG Debug Exception

An EJTAG Debug Exception occurs when one of a number of EJTAG-related conditions is met. Refer to the EJTAG Specification for details of this exception.

Entry Vector Used

16#BFC0 0480 if the ProbEn bit is zero in the EJTAG_Control_register; 16#FF20 0200 if the ProbEn bit is one.

5.2.4 Reset Exception

A Reset Exception occurs when the Cold 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, only the following registers have defined state:

- The *Random* register is initialized to the number of TLB entries - 1.
- The *Wired* register is initialized to zero.
- The *Config, Config1, Config2,* and *Config3* registers are initialized with their boot state.
- The RP, BEV, TS, SR, NMI, and ERL fields of the *Status* register are initialized to a specified state.
- Watch register enables and Performance Counter register interrupt enables are cleared.
- The *ErrorEPC* register is loaded with the restart PC, as described in Table 5-5. Note that this value may or may not be predictable if the Reset Exception was taken as the result of power being applied to the processor because PC may not have a valid value in that case. In some implementations, the value loaded into *ErrorEPC* register may not be predictable on either a Reset or Soft Reset Exception.
- PC is loaded with 16#BFC0 0000.

***Cause* Register ExcCode Value**

None

Additional State Saved

None

Entry Vector Used

Reset (16#BFC0 0000)

Operation

```
Random ← TLBEntries - 1
Wired ← 0
Config ← ConfigurationState
Config_K0 ← 2                  # Suggested - see Config register description
Config1 ← ConfigurationState
Config2 ← ConfigurationState  # if implemented
Config3 ← ConfigurationState  # if implemented
Status_RP ← 0
Status_BEV ← 1
Status_TS ← 0
Status_SR ← 0
Status_NMI ← 0
Status_ERL ← 1
WatchLo[n]_I ← 0               # For all implemented Watch registers
WatchLo[n]_R ← 0               # For all implemented Watch registers
WatchLo[n]_W ← 0               # For all implemented Watch registers
PerfCnt.Control[n]_IE ← 0      # For all implemented PerfCnt registers
if InstructionInBranchDelaySlot then
   ErrorEPC ← restartPC # PC of branch/jump
else
   ErrorEPC ← restartPC # PC of instruction
endif
PC ← 16#BFC0 0000
```

5.2.5 Soft Reset Exception

A Soft Reset Exception occurs when the Reset signal is asserted to the processor. This exception is not maskable. When a Soft Reset Exception occurs, the processor performs a subset of the full reset initialization. Although a Soft Reset Exception does not unnecessarily change the state of the processor, it may be forced to do so in order to place the processor in a state in which it can execute instructions from uncached, unmapped address space. Since bus, cache, or other operations may be interrupted, portions of the cache, memory, or other processor state may be inconsistent. In addition to any hardware initialization required, the following state is established on a Soft Reset Exception:

- The RP, BEV, TS, SR, NMI, and ERL fields of the *Status* register are initialized to a specified state.
- Watch register enables and Performance Counter register interrupt enables are cleared.
- The *ErrorEPC* register is loaded with the restart PC, as described in Table 5-5.
- PC is loaded with `16#BFC0 0000`.

***Cause* Register ExcCode Value**

None

Additional State Saved

None

Entry Vector Used

Reset (`16#BFC0 0000`)

Operation

```
Config_K0 ← 2                  # Suggested - see Config register description
Status_RP ← 0
Status_BEV ← 1
Status_TS ← 0
Status_SR ← 1
Status_NMI ← 0
Status_ERL ← 1
WatchLo[n]_I ← 0               # For all implemented Watch registers
WatchLo[n]_R ← 0               # For all implemented Watch registers
WatchLo[n]_W ← 0               # For all implemented Watch registers
PerfCnt.Control[n]_IE ← 0      # For all implemented PerfCnt registers
if InstructionInBranchDelaySlot then
   ErrorEPC ← restartPC # PC of branch/jump
else
   ErrorEPC ← restartPC # PC of instruction
endif
PC ← 16#BFC0 0000
```

5.2.6 Non Maskable Interrupt (NMI) Exception

A non maskable interrupt exception occurs when the NMI signal is asserted to the processor.

Unlike all other interrupts, this exception is not maskable. An NMI occurs only at instruction boundaries, so does not do any reset or other hardware initialization. The state of the cache, memory, and other processor state is 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 restart PC, as described in Table 5-5.
- PC is loaded with `16#BFC0 0000`.

Cause Register ExcCode Value

None

Additional State Saved

None

Entry Vector Used

Reset (`16#BFC0 0000`)

Operation

```
StatusBEV ← 1
StatusTS ← 0
StatusSR ← 0
StatusNMI ← 1
StatusERL ← 1
if InstructionInBranchDelaySlot then
   ErrorEPC ← restartPC # PC of branch/jump
else
   ErrorEPC ← restartPC # PC of instruction
endif
PC ← 16#BFC0 0000
```

5.2.7 Machine Check Exception

A machine check exception occurs when the processor detects an internal inconsistency.

The following conditions cause a machine check exception:

- Detection of multiple matching entries in the TLB in a TLB-based MMU.

***Cause* Register ExcCode Value**

MCheck (See Table 6-17 on page 59)

Additional State Saved

Depends on the condition that caused the exception. See the descriptions above.

Entry Vector Used

General exception vector (offset 16#180)

5.2.8 Address Error Exception

An address error exception occurs under the following circumstances:

- An instruction is fetched from an address that is not aligned on a word boundary.
- A load or store word instruction is executed in which the address is not aligned on a word boundary.
- A load or store halfword instruction is executed in which the address is not aligned on a halfword boundary.
- A reference is made to a kernel address space from User Mode or Supervisor Mode.
- A reference is made to a supervisor address space from User Mode.

Note that in the case of an instruction fetch that is not aligned on a word boundary, the PC is updated before the condition is detected. Therefore, both EPC and BadVAddr point at the unaligned instruction address.

***Cause* Register ExcCode Value**

AdEL: Reference was a load or an instruction fetch

AdES: Reference was a store

See Table 6-17 on page 59.

Additional State Saved

Register State	Value
BadVAddr	failing address
$Context_{VPN2}$	UNPREDICTABLE
$EntryHi_{VPN2}$	UNPREDICTABLE
EntryLo0	UNPREDICTABLE
EntryLo1	UNPREDICTABLE

Entry Vector Used

General exception vector (offset 16#180)

5.2.9 TLB Refill Exception

A TLB Refill exception occurs in a TLB-based MMU when no TLB entry matches a reference to a mapped address space and the EXL bit is zero in the *Status* register. Note that this is distinct from the case in which an entry matches but has the valid bit off, in which case a TLB Invalid exception occurs.

***Cause* Register ExcCode Value**

TLBL: Reference was a load or an instruction fetch

TLBS: Reference was a store

See Table 6-17 on page 59.

Additional State Saved

Register State	Value
BadVAddr	failing address
Context	The BadVPN2 field contains $VA_{31..13}$ of the failing address
EntryHi	The VPN2 field contains $VA_{31..13}$ of the failing address; the ASID field contains the ASID of the reference that missed.
EntryLo0	UNPREDICTABLE
EntryLo1	UNPREDICTABLE

Entry Vector Used

- TLB Refill vector (offset 16#000) if $Status_{EXL}$ = 0 at the time of exception.
- General exception vector (offset 16#180) if $Status_{EXL}$ = 1 at the time of exception

5.2.10 TLB Invalid Exception

A TLB invalid exception occurs when a TLB entry matches a reference to a mapped address space, but the matched entry has the valid bit off.

Note that the condition in which no TLB entry matches a reference to a mapped address space and the EXL bit is one in the *Status* register is indistinguishable from a TLB Invalid Exception in the sense that both use the general exception vector and supply an ExcCode value of TLBL or TLBS. The only way to distinguish these two cases is by probing the TLB for a matching entry (using TLBP).

***Cause* Register ExcCode Value**

TLBL: Reference was a load or an instruction fetch

TLBS: Reference was a store

See Table 6-16 on page 58.

Additional State Saved

Register State	Value
BadVAddr	failing address
Context	The BadVPN2 field contains $VA_{31..13}$ of the failing address
EntryHi	The VPN2 field contains $VA_{31..13}$ of the failing address; the ASID field contains the ASID of the reference that missed.
EntryLo0	UNPREDICTABLE
EntryLo1	UNPREDICTABLE

Entry Vector Used

General exception vector (offset 16#180)

5.2.11 TLB Modified Exception

A TLB modified exception occurs on a *store* reference to a mapped address when the matching TLB entry is valid, but the entry's D bit is zero, indicating that the page is not writable.

***Cause* Register ExcCode Value**

Mod (See Table 6-16 on page 58)

Additional State Saved

Register State	Value
BadVAddr	failing address
Context	The BadVPN2 field contains $VA_{31..13}$ of the failing address
EntryHi	The VPN2 field contains $VA_{31..13}$ of the failing address; the ASID field contains the ASID of the reference that missed.
EntryLo0	UNPREDICTABLE
EntryLo1	UNPREDICTABLE

Entry Vector Used

General exception vector (offset 16#180)

5.2.12 Cache Error Exception

A cache error exception occurs when an instruction or data reference detects a cache tag or data error, or a parity or ECC error is detected on the system bus when a cache miss occurs. This exception is not maskable. Because the error was in a cache, the exception vector is to an unmapped, uncached address.

***Cause* Register ExcCode Value**

N/A

Additional State Saved

Register State	Value
CacheErr	Error state
ErrorEPC	Restart PC

Entry Vector Used

Cache error vector (offset 16#100)

Operation

```
CacheErr ← ErrorState
Status_ERL ← 1
if InstructionInBranchDelaySlot then
   ErrorEPC ← restartPC # PC of branch/jump
else
   ErrorEPC ← restartPC # PC of instruction
endif
if Status_BEV = 1 then
   PC ← 16#BFC0 0200 + 16#100
else
   PC ← 16#A000 0000 + 16#100
endif
```

5.2.13 Bus Error Exception

A bus error occurs when an instruction, data, or prefetch access makes a bus request (due to a cache miss or an uncacheable reference) and that request is terminated in an error. Note that parity errors detected during bus transactions are reported as cache error exceptions, not bus error exceptions.

***Cause* Register ExcCode Value**

IBE: Error on an instruction reference

DBE: Error on a data reference

See Table 6-17 on page 59.

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.14 Integer Overflow Exception

An integer overflow exception occurs when selected integer instructions result in a 2’s complement overflow.

***Cause* Register ExcCode Value**

Ov (See Table 6-17 on page 59)

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.15 Trap Exception

A trap exception occurs when a trap instruction results in a TRUE value.

***Cause* Register ExcCode Value**

Tr (See Table 6-17 on page 59)

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.16 System Call Exception

A system call exception occurs when a SYSCALL instruction is executed.

***Cause* Register ExcCode Value**

Sys (See Table 6-16 on page 58)

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.17 Breakpoint Exception

A breakpoint exception occurs when a BREAK instruction is executed.

***Cause* Register ExcCode Value**

Bp (See Table 6-17 on page 59)

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.18 Reserved Instruction Exception

A Reserved Instruction Exception occurs if any of the following conditions is true:

- An instruction was executed that specifies an encoding of the opcode field that is flagged with “*” (reserved), “β” (higher-order ISA), or an unimplemented “ε” (ASE).

- An instruction was executed that specifies a *SPECIAL* opcode encoding of the function field that is flagged with "∗" (reserved), or "β" (higher-order ISA).
- An instruction was executed that specifies a *REGIMM* opcode encoding of the rt field that is flagged with "∗" (reserved).
- An instruction was executed that specifies an unimplemented *SPECIAL2* opcode encoding of the function field that is flagged with an unimplemented "θ" (partner available), or an unimplemented "σ" (EJTAG).
- An instruction was executed that specifies a *COPz* opcode encoding of the rs field that is flagged with "∗" (reserved), "β" (higher-order ISA), or an unimplemented "ε" (ASE), assuming that access to the coprocessor is allowed. If access to the coprocessor is not allowed, a Coprocessor Unusable Exception occurs instead. For the *COP1* opcode, some implementations of previous ISAs reported this case as a Floating Point Exception, setting the Unimplemented Operation bit in the Cause field of the *FCSR* register.
- An instruction was executed that specifies an unimplemented *COP0* opcode encoding of the function field when rs is *CO* that is flagged with "∗" (reserved), or an unimplemented "σ" (EJTAG), assuming that access to coprocessor 0 is allowed. If access to the coprocessor is not allowed, a Coprocessor Unusable Exception occurs instead.
- An instruction was executed that specifies a *COP1* opcode encoding of the function field that is flagged with "∗" (reserved), "β" (higher-order ISA), or an unimplemented "ε" (ASE), assuming that access to coprocessor 1 is allowed. If access to the coprocessor is not allowed, a Coprocessor Unusable Exception occurs instead. Some implementations of previous ISAs reported this case as a Floating Point Exception, setting the Unimplemented Operation bit in the Cause field of the *FCSR* register.

***Cause* Register ExcCode Value**

RI (See Table 6-17 on page 59)

Additional State Saved

None

Entry Vector Used

General exception vector (offset 16#180)

5.2.19 Coprocessor Unusable Exception

A coprocessor unusable exception occurs if any of the following conditions is true:

- A COP0 or Cache instruction was executed while the processor was running in a mode other than Debug Mode or Kernel Mode, and the CU0 bit in the *Status* register was a zero
- A COP1, LWC1, SWC1, LDC1, SDC1 or MOVCI (Special opcode function field encoding) instruction was executed and the CU1 bit in the *Status* register was a zero.
- A COP2, LWC2, SWC2, LDC2, or SDC2 instruction was executed, and the CU2 bit in the *Status* register was a zero.
- A COP3 instruction was executed, and the CU3 bit in the *Status* register was a zero.

***Cause* Register ExcCode Value**

CpU (See Table 6-16 on page 58)

Additional State Saved

Register State	Value
$Cause_{CE}$	unit number of the coprocessor being referenced

Entry Vector Used

General exception vector (offset 16#180)

5.2.20 Floating Point Exception

A floating point exception is initiated by the floating point coprocessor to signal a floating point exception.

Register ExcCode Value

FPE (See Table 6-16 on page 58)

Additional State Saved

Register State	Value
FCSR	indicates the cause of the floating point exception

Entry Vector Used

General exception vector (offset 16#180)

5.2.21 Coprocessor 2 Exception

A coprocessor 2 exception is initiated by coprocessor 2 to signal a precise coprocessor 2 exception.

Register ExcCode Value

C2E (See Table 6-16 on page 58)

Additional State Saved

Defined by the coprocessor

Entry Vector Used

General exception vector (offset 16#180)

5.2.22 Watch Exception

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. If either bit is a one at the time that a watch exception would normally be taken, the WP bit in the *Cause* register is set, and the exception is deferred until both the EXL and ERL bits in the Status register 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.

If the EXL or ERL bits are one in the *Status* register and a single instruction generates both a watch exception (which is deferred by the state of the EXL and ERL bits) and a lower-priority exception, the lower priority exception is taken.

Watch exceptions are never taken if the processor is executing in Debug Mode. Should a watch register match while the processor is in Debug Mode, the exception is inhibited and the WP bit is not changed.

It is implementation dependent whether a data watch exception is triggered by a prefetch or cache instruction whose address matches the Watch register address match conditions.

Register ExcCode Value

WATCH (See Table 6-16 on page 58)

Additional State Saved

Register State	Value
$Cause_{WP}$	indicates that the watch exception was deferred until after both $Status_{EXL}$ and $Status_{ERL}$ 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.

Entry Vector Used

General exception vector (offset 16#180)

5.2.23 Interrupt Exception

The interrupt exception occurs when one or more of the eight interrupt requests is enabled by the Status registers. See Section 5.1 on page 21 for more information.

Register ExcCode Value

Int (See Table 6-17 on page 59)

Additional State Saved

Register State	Value
$Cause_{IP}$	indicates the interrupts that are pending.

Entry Vector Used

General exception vector (offset 16#180) if the IV bit in the *Cause* register is zero.

Interrupt vector (offset 16#200) if the IV bit in the *Cause* register is one.

Coprocessor 0 Registers

The Coprocessor 0 (CP0) registers provide the interface between the ISA and the PRA. Each register is discussed below, with the registers presented in numerical order, first by register number, then by select field number.

6.1 Coprocessor 0 Register Summary

Table 6-1 lists the CP0 registers in numerical order. The individual registers are described later in this document. If the compliance level is qualified (e.g., "*Required* (TLB MMU)"), it applies only if the qualifying condition is true. The Sel column indicates the value to be used in the field of the same name in the MFC0 and MTC0 instructions.

Table 6-1 Coprocessor 0 Registers in Numerical Order

Register Number	Sel	Register Name	Function	Reference	Compliance Level
0	0	Index	Index into the TLB array	Section 6.3 on page 41	Required (TLB MMU); Optional (others)
1	0	Random	Randomly generated index into the TLB array	Section 6.4 on page 42	Required (TLB MMU); Optional (others)
2	0	EntryLo0	Low-order portion of the TLB entry for even-numbered virtual pages	Section 6.5 on page 43	Required (TLB MMU); Optional (others)
3	0	EntryLo1	Low-order portion of the TLB entry for odd-numbered virtual pages	Section 6.5 on page 43	Required (TLB MMU); Optional (others)
4	0	Context	Pointer to page table entry in memory	Section 6.6 on page 45	Required (TLB MMU); Optional (others)
5	0	PageMask	Control for variable page size in TLB entries	Section 6.7 on page 46	Required (TLB MMU); Optional (others)
6	0	Wired	Controls the number of fixed ("wired") TLB entries	Section 6.8 on page 47	Required (TLB MMU); Optional (others)
7	all		Reserved for future extensions		Reserved
8	0	BadVAddr	Reports the address for the most recent address-related exception	Section 6.9 on page 48	Required
9	0	Count	Processor cycle count	Section 6.10 on page 49	Required
9	6-7		Available for implementation dependent user	Section 6.11 on page 49	Implementation Dependent

Table 6-1 Coprocessor 0 Registers in Numerical Order

Register Number	Sel	Register Name	Function	Reference	Compliance Level
10	0	EntryHi	High-order portion of the TLB entry	Section 6.12 on page 51	Required (TLB MMU); Optional (others)
11	0	Compare	Timer interrupt control	Section 6.13 on page 52	Required
11	6-7		Available for implementation dependent user	Section 6.14 on page 52	Implementation Dependent
12	0	Status	Processor status and control	Section 6.15 on page 53	Required
13	0	Cause	Cause of last general exception	Section 6.16 on page 58	Required
14	0	EPC	Program counter at last exception	Section 6.17 on page 61	Required
15	0	PRId	Processor identification and revision	Section 6.18 on page 62	Required
16	0	Config	Configuration register	Section 6.19 on page 63	Required
16	1	Config1	Configuration register 1	Section 6.20 on page 65	Required
16	2	Config2	Configuration register 2	Section 6.21 on page 69	Optional
16	3	Config3	Configuration register 3	Section 6.22 on page 70	Optional
16	6-7		Available for implementation dependent user	Section 6.23 on page 71	Implementation Dependent
17	0	LLAddr	Load linked address	Section 6.24 on page 72	Optional
18	0-n	WatchLo	Watchpoint address	Section 6.25 on page 73	Optional
19	0-n	WatchHi	Watchpoint control	Section 6.26 on page 74	Optional
20	0		XContext in 64-bit implementations		Reserved
21	all		Reserved for future extensions		Reserved
22	all		Available for implementation dependent use	Section 6.27 on page 76	Implementation Dependent
23	0	Debug	EJTAG Debug register	EJTAG Specification	Optional
24	0	DEPC	Program counter at last EJTAG debug exception	EJTAG Specification	Optional
25	0-n	PerfCnt	Performance counter interface	Section 6.30 on page 79	Recommended
26	0	ErrCtl	Parity/ECC error control and status	Section 6.31 on page 82	Optional

Table 6-1 Coprocessor 0 Registers in Numerical Order

Register Number	Sel	Register Name	Function	Reference	Compliance Level
27	0-3	CacheErr	Cache parity error control and status	Section 6.32 on page 83	Optional
28	0	TagLo	Low-order portion of cache tag interface	Section 6.33 on page 84	Required (Cache)
28	1	DataLo	Low-order portion of cache data interface	Section 6.34 on page 85	Optional
29	0	TagHi	High-order portion of cache tag interface	Section 6.35 on page 86	Required (Cache)
29	1	DataHi	High-order portion of cache data interface	Section 6.36 on page 87	Optional
30	0	ErrorEPC	Program counter at last error	Section 6.37 on page 88	Required
31	0	DESAVE	EJTAG debug exception save register	EJTAG Specification	Optional

6.2 Notation

For each register described below, field descriptions include the read/write properties of the field, and the reset state of the field. For the read/write properties of the field, the following notation is used:

Table 6-2 Read/Write Bit Field Notation

Read/Write Notation	Hardware Interpretation	Software Interpretation
R/W	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 read. Software updates of this field are visible by hardware read. 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.	
R	A field which is either static or is updated only by hardware. 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. 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.

Table 6-2 Read/Write Bit Field Notation

Read/Write Notation	Hardware Interpretation	Software Interpretation
0	A field which 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.

6.3 Index Register (CP0 Register 0, Select 0)

Compliance Level: *Required* for TLB-based MMUs; *Optional* otherwise.

The *Index* register is a 32-bit read/write register which 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 Ceiling(Log2(TLBEntries)). For example, six bits are required for a TLB with 48 entries).

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.

Figure 6-1 shows the format of the *Index* register; Table 6-3 describes the *Index* register fields.

Figure 6-1 Index Register Format

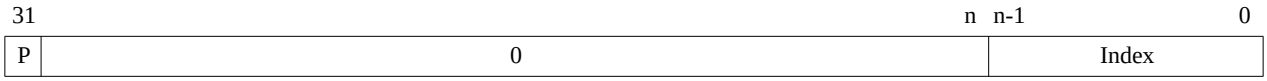


Table 6-3 Index Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	**Bits**				
P	31	Probe Failure. Hardware writes this bit during execution of the TLBP instruction to indicate whether a TLB match occurred: **Encoding** / **Meaning** 0 — A match occurred, and the Index field contains the index of the matching entry 1 — No match occurred and the Index field is **UNPREDICTABLE**	R	Undefined	Required
0	30..n	Must be written as zero; returns zero on read.	0	0	Reserved
Index	n-1..0	TLB index. Software writes this field to provide the index to the TLB entry referenced by the TLBR and TLBWI instructions. Hardware writes this field with the index of the matching TLB entry during execution of the TLBP instruction. If the TLBP fails to find a match, the contents of this field are **UNPREDICTABLE**.	R/W	Undefined	Required

6.4 Random Register (CP0 Register 1, Select 0)

Compliance Level: *Required* for TLB-based MMUs; *Optional* otherwise.

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.

Within the required constraints of the upper and lower bounds, the manner in which the processor selects values for the Random register is implementation-dependent.

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

Figure 6-2 shows the format of the *Random* register; Table 6-4 describes the *Random* register fields.

Figure 6-2 Random Register Format

Table 6-4 Random Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
0	31..n	Must be written as zero; returns zero on read.	0	0	Reserved
Random	n-1..0	TLB Random Index	R	TLB Entries - 1	Required

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

Compliance Level: EntryLo0 is *Required* for a TLB-based MMU; *Optional* otherwise.

Compliance Level: EntryLo1 is *Required* for a TLB-based MMU; *Optional* otherwise.

The pair of EntryLo registers act as the interface between the TLB and the TLBP, TLBR, TLBWI, and TLBWR instructions. EntryLo0 holds the entries for even pages and EntryLo1 holds the entries for odd pages.

The contents of the EntryLo0 and EntryLo1 registers are not defined after an address error exception and some fields may be modified by hardware during the address error exception sequence. Software writes of the *EntryHi* register (via MTC0) do not cause the implicit update of address-related fields in the *BadVAddr* or *Context* registers.

Figure 6-3 shows the format of the EntryLo0 and EntryLo1 registers; Table 6-5 describes the EntryLo0 and EntryLo1 register fields.

Figure 6-3 EntryLo0, EntryLo1 Register Format

Table 6-5 EntryLo0, EntryLo1 Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
0	31..30	Ignored on write; returns zero on read.	R	0	Required
PFN	29..6	Page Frame Number. Corresponds to bits*PABITS*-1..12 of the physical address, where *PABITS* is the width of the physical address in bits.	R/W	Undefined	Required
C	5..3	Coherency attribute of the page. See Table 6-6 below.	R/W	Undefined	Required
D	2	"Dirty" bit, indicating that the page is writable. If this bit is a one, stores to the page are permitted. If this bit is a zero, stores to the page cause a TLB Modified exception. Kernel software may use this bit to implement paging algorithms that require knowing which pages have been written. If this bit is always zero when a page is initially mapped, the TLB Modified exception that results on any store to the page can be used to update kernel data structures that indicate that the page was actually written.	R/W	Undefined	Required
V	1	Valid bit, indicating that the TLB entry, and thus the virtual page mapping are valid. If this bit is a one, accesses to the page are permitted. If this bit is a zero, accesses to the page cause a TLB Invalid exception.	R/W	Undefined	Required
G	0	Global bit. On a TLB write, the logical AND of the G bits from both EntryLo0 and EntryLo1 becomes the G bit in the TLB entry. If the TLB entry G bit is a one, ASID comparisons are ignored during TLB matches. On a read from a TLB entry, the G bits of both EntryLo0 and EntryLo1 reflect the state of the TLB G bit.	R/W	Undefined	Required (TLB MMU)

Table 6-6 lists the encoding of the C field of the *EntryLo0* and *EntryLo1* registers and the K0 field of the *Config* register. An implementation may choose to implement a subset of the cache coherency attributes shown, but must implement at

least encodings 2 and 3 such that software can always depend on these encodings working appropriately. In other cases, the operation of the processor is **UNDEFINED** if software specifies an unimplemented encoding.

Table 6-6 lists the required and optional encodings for the coherency attributes.

Table 6-6 Cache Coherency Attributes

C(5:3) Value	Cache Coherency Attributes With Historical Usage	Compliance
0	Available for implementation dependent use	Optional
1	Available for implementation dependent use	Optional
2	Uncached	Required
3	Cacheable	Required
4	Available for implementation dependent use	Optional
5	Available for implementation dependent use	Optional
6	Available for implementation dependent use	Optional
7	Available for implementation dependent use	Optional

6.6 Context Register (CP0 Register 4, Select 0)

Compliance Level: *Required* for TLB-based MMUs; *Optional* otherwise.

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 a 16-byte structure in memory that describes the mapping.

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 and this field may be modified by hardware during the address error exception sequence.

Figure 6-4 shows the format of the *Context* Register; Table 6-7 describes the *Context* register fields.

Figure 6-4 Context Register Format

Table 6-7 Context Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
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	Required
BadVPN2	22..4	This field is written by hardware on a TLB exception. It contains bits $VA_{31..13}$ of the virtual address that caused the exception.	R	Undefined	Required
0	3..0	Must be written as zero; returns zero on read.	0	0	Reserved

6.7 PageMask Register (CP0 Register 5, Select 0)

Compliance Level: *Required* for TLB-based MMUs; *Optional* otherwise.

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 6-9. Figure 6-5 shows the format of the *PageMask* register; Table 6-8 describes the *PageMask* register fields.

Figure 6-5 PageMask Register Format

Table 6-8 PageMask Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
Mask	28..13	The Mask 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	Required
0	31..29, 12..0	Must be written as zero; returns zero on read.	0	0	Reserved

Table 6-9 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

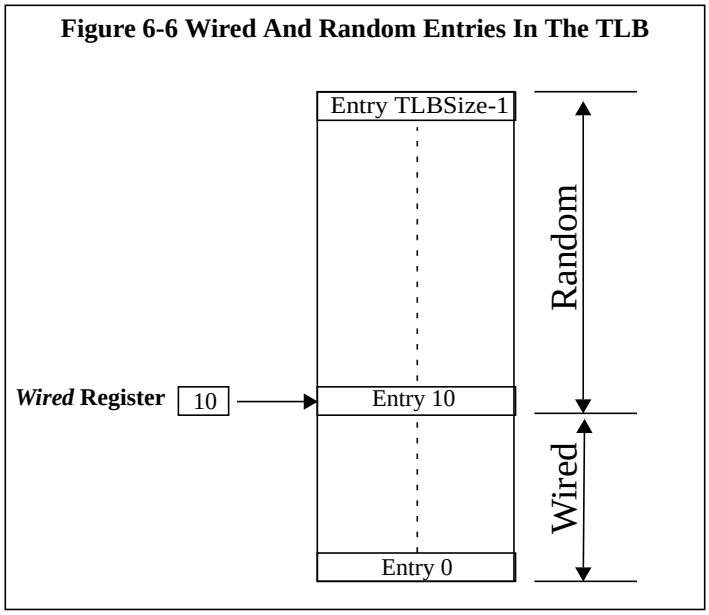
It is implementation dependent how many of the encodings described in Table 6-9 are implemented. All processors must implement the 4KB page size (an encoding of all zeros). If a particular page size encoding is not implemented by a processor, a read of the *PageMask* register must return zeros in all bits that correspond to encodings that are not implemented. Software may determine which page sizes are supported by writing the encoding for a 256MB page to the *PageMask* register, then examine the value returned from a read of the *PageMask* register. 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 PageMask register with a value other than one of those listed in Table 6-9.

6.8 Wired Register (CP0 Register 6, Select 0)

Compliance Level: *Required* for TLB-based MMUs; *Optional* otherwise.

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 6-6.

Figure 6-6 Wired And Random Entries In The TLB



The width of the Wired field is calculated in the same manner as that described for the *Index* register. Wired entries are fixed, non-replaceable entries which are not overwritten by a TLBWR instruction.Wired entries can be overwritten by a TLBWI instruction.

The *Wired* register is set 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.

Figure 6-6 shows the format of the *Wired* register; Table 6-10 describes the *Wired* register fields.

Figure 6-7 Wired Register Format

Table 6-10 Wired Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
0	31..n	Must be written as zero; returns zero on read.	0	0	Reserved
Wired	n-1..0	TLB wired boundary	R/W	0	Required

6.9 BadVAddr Register (CP0 Register 8, Select 0)

Compliance Level: *Required*.

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 (TLBL, TLBS)
- TLB Modified

The *BadVAddr* register does not capture address information for cache or bus errors, or for Watch exceptions, since none is an addressing error.

Figure 6-8 shows the format of the *BadVAddr* register; Table 6-11 describes the BadVAddr register fields.

Figure 6-8 BadVAddr Register Format

Table 6-11 BadVAddr Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
BadVAddr	31..0	Bad virtual address	R	Undefined	Required

6.10 Count Register (CP0 Register 9, Select 0)

Compliance Level: *Required.*

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. The rate at which the counter increments is implementation dependent, and is a function of the pipeline clock of the processor, not the issue width of the processor.

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

Figure 6-9 shows the format of the Count register; Table 6-12 describes the Count register fields.

Figure 6-9 Count Register Format

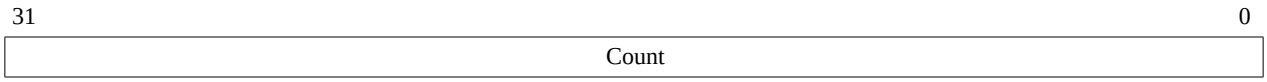


Table 6-12 Count Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
Count	31..0	Interval counter	R/W	Undefined	Required

6.11 Reserved for Implementations (CP0 Register 9, Selects 6 and 7)

Compliance Level: *Optional: Implementation Dependent.*

CP0 register 9, Selects 6 and 7 are reserved for implementation dependent use and are not defined by the architecture.

6.12 EntryHi Register (CP0 Register 10, Select 0)

Compliance Level: *Required* for TLB-based MMU; *Optional* otherwise.

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. 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.

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.

Figure 6-10 shows the format of the *EntryHi* register; Table 6-13 describes the *EntryHi* register fields.

Figure 6-10 EntryHi Register Format

Table 6-13 EntryHi Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
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	Required
0	12..8	Must be written as zero; returns zero on read.	0	0	Reserved
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	Required (TLB MMU)

6.13 Compare Register (CP0 Register 11, Select 0)

Compliance Level: *Required.*

The *Compare* register acts in conjunction with the *Count* register to implement a timer and timer interrupt function. 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, an interrupt request is combined in an implementation-dependent way with hardware interrupt 5 to set interrupt bit IP(7) in the *Cause* register. This causes an interrupt as soon as the interrupt is enabled.

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 6-11 shows the format of the *Compare* register; Table 6-14 describes the Compare register fields.

Figure 6-11 Compare Register Format

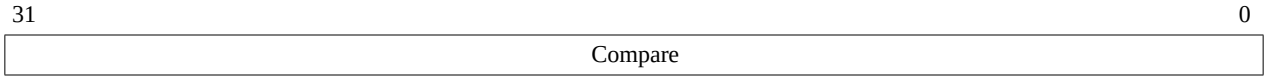


Table 6-14 Compare Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
Compare	31..0	Interval count compare value	R/W	Undefined	Required

6.14 Reserved for Implementations (CP0 Register 11, Selects 6 and 7)

Compliance Level: *Optional: Implementation Dependent.*

CP0 register 11, Selects 6 and 7 are reserved for implementation dependent use and are not defined by the architecture.

6.15 Status Register (CP Register 12, Select 0)

Compliance Level: *Required.*

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 Chapter 3, "MIPS32 Operating Modes," on page 9 for a discussion of operating modes, and Section 5.1 on page 21 for a discussion of interrupt enable.

Figure 6-12 shows the format of the Status register; Table 6-15 describes the Status register fields.

Figure 6-12 Status Register Format

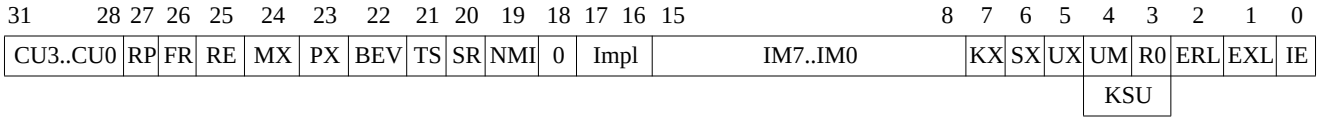


Table 6-15 Status Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	**Bits**				
CU (CU3.. CU0)	31..28	Controls access to coprocessors 3, 2, 1, and 0, respectively: **Encoding** / **Meaning** 0 — Access not allowed 1 — Access allowed Coprocessor 0 is always usable when the processor is running in Kernel Mode or Debug Mode, independent of the state of the CU_0 bit. If there is no provision for connecting a coprocessor, the corresponding CU bit must be ignored on write and read as zero.	R/W	Undefined	Required for all implemented coprocessors
RP	27	Enables reduced power mode on some implementations. The specific operation of this bit is implementation dependent. If this bit is not implemented, it must be ignored on write and read as zero. If this bit is implemented, the reset state must be zero so that the processor starts at full performance.	R/W	0	Optional
FR	26	Controls the floating point register mode on MIPS64 processors. Not used by MIPS32 processors. This bit must be ignored on write and read as zero.	R	0	Required

Table 6-15 Status Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>RE</td><td>25</td><td>Used to enable reverse-endian memory references while the processor is running in user mode:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>User mode uses configured endianness</td></tr><tr><td>1</td><td>User mode uses reversed endianness</td></tr></table>
Neither Debug Mode nor Kernel Mode nor Supervisor Mode references are affected by the state of this bit.

If this bit is not implemented, it must be ignored on write and read as zero.</td><td>R/W</td><td>Undefined</td><td>Optional</td></tr>
<tr><td>MX</td><td>24</td><td>Enables access to MDMX™ resources on MIPS64 processors. Not used by MIPS32 processors. This bit must be ignored on write and read as zero.</td><td>R</td><td>0</td><td>Optional</td></tr>
<tr><td>PX</td><td>23</td><td>Enables access to 64-bit operations on MIPS64 processors. Not used by MIPS32 processors. This bit must be ignored on write and read as zero.</td><td>R</td><td>0</td><td>Required</td></tr>
<tr><td>BEV</td><td>22</td><td>Controls the location of exception vectors:
<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>
See Section 5.2.1 on page 22 for details.</td><td>R/W</td><td>1</td><td>Required</td></tr>
<tr><td>TS</td><td>21</td><td>Indicates that the TLB has detected a match on multiple entries. When such a detection occurs, the processor initiates a machine check exception and sets this bit. It is implementation dependent whether this condition can be corrected by software. If the condition can be corrected, this bit should be cleared by software before resuming normal operation.

If this bit is not implemented, it must be ignored on write and read as zero.

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 machine check exception.</td><td>R/W</td><td>0</td><td>Required if TLB Shutdown is implemented</td></tr>
</table>

Table 6-15 Status Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>SR</td><td>20</td><td>Indicates that the entry through the reset exception vector was due to a Soft Reset:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Not Soft Reset (NMI or Reset)</td></tr><tr><td>1</td><td>Soft Reset</td></tr></table>If this bit is not implemented, it must be ignored on write and read as zero.
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 or accepts the write.</td><td>R/W</td><td>1 for Soft Reset; 0 otherwise</td><td>Required if Soft Reset is implemented</td></tr>
<tr><td>NMI</td><td>19</td><td>Indicates that the entry through the reset exception vector was due to an NMI:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Not NMI (Soft Reset or Reset)</td></tr><tr><td>1</td><td>NMI</td></tr></table>If this bit is not implemented, it must be ignored on write and read as zero.
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 or accepts the write.</td><td>R/W</td><td>1 for NMI; 0 otherwise</td><td>Required if NMI is implemented</td></tr>
<tr><td>0</td><td>18</td><td>Must be written as zero; returns zero on read.</td><td>0</td><td>0</td><td>Reserved</td></tr>
<tr><td>Impl</td><td>17..16</td><td>These bits are implementation dependent and are not defined by the architecture. If they are not implemented, they must be ignored on write and read as zero.</td><td></td><td>Undefined</td><td>Optional</td></tr>
<tr><td>IM7:IM0</td><td>15..8</td><td>Interrupt Mask: Controls the enabling of each of the external, internal and software interrupts. Refer to Section 5.1 on page 21 for a complete discussion of enabled interrupts.
<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></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>KX</td><td>7</td><td>Enables access to 64-bit kernel address space on 64-bit MIPS processors. Not used by MIPS32 processors. This bit must be ignored on write and read as zero.</td><td>R</td><td>0</td><td>Reserved</td></tr>
<tr><td>SX</td><td>6</td><td>Enables access to 64-bit supervisor address space on 64-bit MIPS processors. Not used by MIPS32 processors. This bit must be ignored on write and read as zero.</td><td>R</td><td>0</td><td>Reserved</td></tr>
</table>

Table 6-15 Status Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>UX</td><td>5</td><td>Enables access to 64-bit user address space on 64-bit MIPS processors Not used by MIPS32 processors. This bit must be ignored on write and read as zero.</td><td>R</td><td>0</td><td>Reserved</td></tr>
<tr><td>KSU</td><td>4..3</td><td>If Supervisor Mode is implemented, the encoding of this field denotes the base operating mode of the processor. See Chapter 3, “MIPS32 Operating Modes,” on page 9 for a full discussion of operating modes. The encoding of this field is:

Note: This field overlaps the UM and R0 fields, described below.</td><td>R/W</td><td>Undefined</td><td>Required if Supervisor Mode is implemented; Optional otherwise</td></tr>
<tr><td>UM</td><td>4</td><td>If Supervisor Mode is not implemented, this bit denotes the base operating mode of the processor. See Chapter 3, “MIPS32 Operating Modes,” on page 9 for a full discussion of operating modes. The encoding of this bit is:

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Base mode is Kernel Mode</td></tr><tr><td>1</td><td>Base mode is User Mode</td></tr></table>
Note: This bit overlaps the KSU field, described above.</td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>R0</td><td>3</td><td>If Supervisor Mode is not implemented, this bit is reserved. This bit must be ignored on write and read as zero.

Note: This bit overlaps the KSU field, described above.</td><td>R</td><td>0</td><td>Reserved</td></tr>
<tr><td>ERL</td><td>2</td><td>Error Level; Set by the processor when a Reset, Soft Reset, NMI or Cache Error exception are taken.

<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>
When ERL is set:
• The processor is running in kernel mode
• Interrupts are disabled
• The ERET instruction will use the return address held in ErrorEPC instead of EPC
• The lower 2^{29} bytes of kuseg are treated as an unmapped and uncached region. See Section 4.6 on page 16. 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.</td><td>R/W</td><td>1</td><td>Required</td></tr>
</table>

Table 6-15 Status Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>EXL</td><td>1</td><td>Exception Level; Set by the processor when any exception other than Reset, Soft Reset, NMI or Cache Error exception are taken.
<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>When EXL is set:
• The processor is running in Kernel Mode
• Interrupts are disabled.
• TLB Refill exceptions use the general exception vector instead of the TLB Refill vector.
• EPC and $Cause_{BD}$ will not be updated if another exception is taken</td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>IE</td><td>0</td><td>Interrupt Enable: Acts as the master enable for software and hardware interrupts:
<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></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
</table>

6.16 Cause Register (CP0 Register 13, Select 0)

Compliance Level: *Required.*

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 $IP_{1:0}$, IV, and WP fields, all fields in the Cause register are read-only.

Figure 6-13 shows the format of the Cause register; Table 6-16 describes the Cause register fields.

Figure 6-13 Cause Register Format

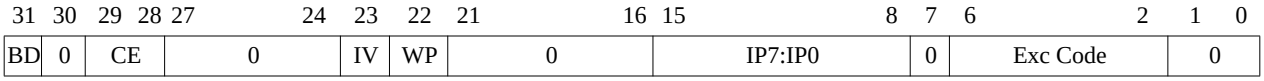


Table 6-16 Cause Register Field Descriptions

Fields		Description	Read/Write	Reset State	Compliance
Name	**Bits**				
BD	31	Indicates whether the last exception taken occurred in a branch delay slot: **Encoding** / **Meaning** 0 — Not in delay slot 1 — In delay slot The processor updates BD only if $Status_{EXL}$ was zero when the exception occurred.	R	Undefined	Required
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	Required
IV	23	Indicates whether an interrupt exception uses the general exception vector or a special interrupt vector: **Encoding** / **Meaning** 0 — Use the general exception vector (16#180) 1 — Use the special interrupt vector (16#200)	R/W	Undefined	Required

Table 6-16 Cause Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>WP</td><td>22</td><td>Indicates that a watch exception was deferred because $Status_{EXL}$ or $Status_{ERL}$ 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 $Status_{EXL}$ and $Status_{ERL}$ 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 $Status_{EXL}$ and $Status_{ERL}$ are both zero.

If watch registers are not implemented, this bit must be ignored on write and read as zero.</td><td>R/W</td><td>Undefined</td><td>Required if watch registers are implemented</td></tr>
<tr><td>IP[7:2]</td><td>15..10</td><td>Indicates an external interrupt is pending:

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>15</td><td>Hardware interrupt 5, timer or performance counter interrupt</td></tr><tr><td>14</td><td>Hardware interrupt 4</td></tr><tr><td>13</td><td>Hardware interrupt 3</td></tr><tr><td>12</td><td>Hardware interrupt 2</td></tr><tr><td>11</td><td>Hardware interrupt 1</td></tr><tr><td>10</td><td>Hardware interrupt 0</td></tr></table></td><td>R</td><td>Undefined</td><td>Required</td></tr>
<tr><td>IP[1:0]</td><td>9..8</td><td>Controls the request for software interrupts:

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>9</td><td>Request software interrupt 1</td></tr><tr><td>8</td><td>Request software interrupt 0</td></tr></table></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>ExcCode</td><td>6..2</td><td>Exception code - see Table 6-17</td><td>R</td><td>Undefined</td><td>Required</td></tr>
<tr><td>0</td><td>30, 27..24, 21..16, 7, 1..0</td><td>Must be written as zero; returns zero on read.</td><td>0</td><td>0</td><td>Reserved</td></tr>
</table>

Table 6-17 Cause Register ExcCode Field

Exception Code Value		Mnemonic	Description
Decimal	Hexadecimal		
0	16#00	Int	Interrupt
1	16#01	Mod	TLB modification exception

Table 6-17 Cause Register ExcCode Field

Exception Code Value		Mnemonic	Description
Decimal	**Hexadecimal**		
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
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
16-17	16#10-16#11	-	Available for implementation dependent use
18	16#12	C2E	Reserved for precise Coprocessor 2 exceptions
19-21	16#13-16#15	-	Reserved
22	16#16	MDMX	Reserved for MDMX Unusable Exception in MIPS64 implementations.
23	16#17	WATCH	Reference to WatchHi/WatchLo address
24	16#18	MCheck	Machine check
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 EJTAG is implemented and a cache error occurs while in Debug Mode, this code is used to indicate that re-entry to Debug Mode was caused by a cache error.
31	16#1f	-	Reserved

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

Compliance Level: *Required.*

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, *EPC* contains either:

- the virtual address of the instruction that was the direct cause of the exception, or
- 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.

For asynchronous (imprecise) exceptions, *EPC* contains the address of the instruction at which to resume execution.

The processor does not write to the *EPC* register when the EXL bit in the *Status* register is set to one.

Figure 6-14 shows the format of the *EPC* register; Table 6-18 describes the *EPC* register fields.

Figure 6-14 EPC Register Format

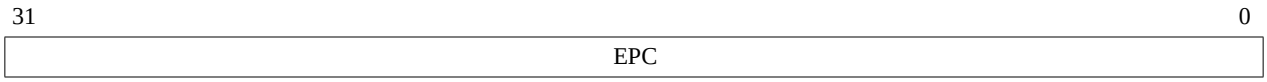


Table 6-18 EPC Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
EPC	31..0	Exception Program Counter	R/W	Undefined	Required

6.17.1 Special Handling of the EPC Register in Processors That Implement the MIPS16 ASE

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

$$GPR[rt] \leftarrow RestartPC_{31..1} \,||\, ISAMode$$

That is, the upper 31 bits of the restart PC are combined with the *ISA Mode* bit 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 restart PC and the *ISA Mode* bit, as follows

$$RestartPC \leftarrow GPR[rt]_{31..1} \,||\, 0$$
$$ISAMode \leftarrow GPR[rt]_{0}$$

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the restart PC, and the lower bit of the restart PC is cleared. The *ISA Mode* bit is loaded from the lower bit of the GPR.

6.18 Processor Identification (CP0 Register 15, Select 0)

Compliance Level: *Required.*

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 6-15 shows the format of the *PRId* register; Table 6-19 describes the *PRId* register fields.

Figure 6-15 PRId Register Format

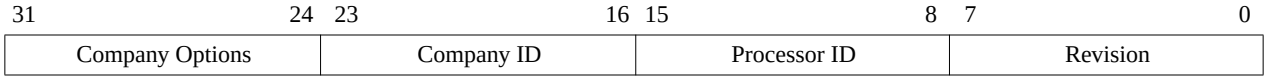


Table 6-19 PRId Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
Company Options	31..24	Available to the designer or manufacturer of the processor for company-dependent options. The value in this field is not specified by the architecture. If this field is not implemented, it must read as zero.	R	Preset	Optional
Company ID	23..16	Identifies the company that designed or manufactured the processor. Software can distinguish a MIPS32 or MIPS64 processor from one implementing an earlier MIPS ISA by checking this field for zero. If it is non-zero the processor implements the MIPS32 or MIPS64 Architecture. Company IDs are assigned by MIPS Technologies when a MIPS32 or MIPS64 license is acquired. The encodings in this field are: **Encoding** / **Meaning** 0 — Not a MIPS32 or MIPS64 processor 1 — MIPS Technologies, Inc. 2-255 — Contact MIPS Technologies, Inc. for the list of Company ID assignments	R	Preset	Required
Processor ID	15..8	Identifies the type of processor. This field allows software to distinguish between various processor implementations within a single company, and is qualified by the CompanyID field, described above. The combination of the CompanyID and ProcessorID fields creates a unique number assigned to each processor implementation.	R	Preset	Required
Revision	7..0	Specifies the revision number of the processor. This field allows software to distinguish between one revision and another of the same processor type. If this field is not implemented, it must read as zero.	R	Preset	Optional

6.19 Configuration Register (CP0 Register 16, Select 0)

Compliance Level: *Required.*

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. One field, K0, must be initialized by software in the reset exception handler.

Figure 6-16 shows the format of the *Config* register; Table 6-20 describes the *Config* register fields.

Figure 6-16 Config Register Format

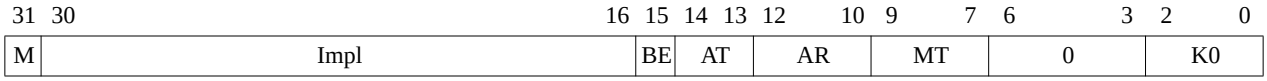


Table 6-20 Config Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	Denotes that the Config1 register is implemented at a select field value of 1.	R	1	Required
Impl	30:16	This field is reserved for implementations. Refer to the processor specification for the format and definition of this field		Undefined	Optional
BE	15	Indicates the endian mode in which the processor is running: Encoding: 0 — Little endian; 1 — Big endian	R	Preset or Externally Set	Required
AT	14:13	Architecture type implemented by the processor: Encoding: 0 — MIPS32; 1 — MIPS64 with access only to 32-bit compatibility segments; 2 — MIPS64 with access to all address segments; 3 — Reserved	R	Preset	Required
AR	12:10	Architecture revision level: Encoding: 0 — Revision 1; 1-7 — Reserved	R	Preset	Required

Table 6-20 Config Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>MT</td><td>9:7</td><td>MMU Type:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>None</td></tr><tr><td>1</td><td>Standard TLB</td></tr><tr><td>2</td><td>Standard BAT (see Section A.1 on page 93)</td></tr><tr><td>3</td><td>Standard fixed mapping (see Section A.2 on page 97)</td></tr><tr><td>4-7</td><td>Reserved</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>K0</td><td>2:0</td><td>Kseg0 coherency algorithm. See Table 6-6 on page 44 for the encoding of this field.</td><td>R/W</td><td>Undefined</td><td>Optional</td></tr>
<tr><td>0</td><td>6:3</td><td>Must be written as zero; returns zero on read.</td><td>0</td><td>0</td><td>Reserved</td></tr>
</table>

6.20 Configuration Register 1 (CP0 Register 16, Select 1)

Compliance Level: *Required.*

The *Config1* register is an adjunct to the *Config* register and encodes additional capabilities information. All fields in the *Config1* register are read-only.

The Icache and Dcache 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:

```
Cache Size = Associativity * Line Size * Sets Per Way
```

If the line size is zero, there is no cache implemented.

Figure 6-17 shows the format of the *Config1* register; Table 6-21 describes the *Config1* register fields.

Figure 6-17 Config1 Register Format

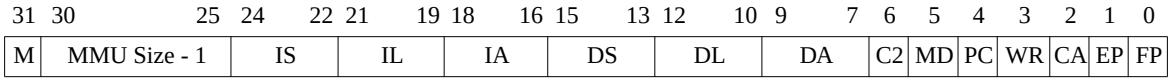


Table 6-21 Config1 Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	This bit is reserved to indicate that a *Config2* register is present. If the *Config2* register is not implemented, this bit should read as a 0. If the *Config2* register is implemented, this bit should read as a 1.	R	Preset	Required
MMU Size - 1	30..25	Number of entries in the TLB minus one. The values 0 through 63 is this field correspond to 1 to 64 TLB entries. The value zero is implied by $Config_{MT}$ having a value of ‘none’.	R	Preset	Required
IS	24:22	Icache sets per way: **Encoding** / **Meaning** 0 – 64 1 – 128 2 – 256 3 – 512 4 – 1024 5 – 2048 6 – 4096 7 – Reserved	R	Preset	Required

Table 6-21 Config1 Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>IL</td><td>21:19</td><td>Icache line size:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No Icache present</td></tr><tr><td>1</td><td>4 bytes</td></tr><tr><td>2</td><td>8 bytes</td></tr><tr><td>3</td><td>16 bytes</td></tr><tr><td>4</td><td>32 bytes</td></tr><tr><td>5</td><td>64 bytes</td></tr><tr><td>6</td><td>128 bytes</td></tr><tr><td>7</td><td>Reserved</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>IA</td><td>18:16</td><td>Icache associativity:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Direct mapped</td></tr><tr><td>1</td><td>2-way</td></tr><tr><td>2</td><td>3-way</td></tr><tr><td>3</td><td>4-way</td></tr><tr><td>4</td><td>5-way</td></tr><tr><td>5</td><td>6-way</td></tr><tr><td>6</td><td>7-way</td></tr><tr><td>7</td><td>8-way</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>DS</td><td>15:13</td><td>Dcache sets per way:
<table><tr><th>Encoding</th><th>Meaning</th></tr><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>Reserved</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
</table>

Table 6-21 Config1 Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>DL</td><td>12:10</td><td>Dcache line size:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No Dcache present</td></tr><tr><td>1</td><td>4 bytes</td></tr><tr><td>2</td><td>8 bytes</td></tr><tr><td>3</td><td>16 bytes</td></tr><tr><td>4</td><td>32 bytes</td></tr><tr><td>5</td><td>64 bytes</td></tr><tr><td>6</td><td>128 bytes</td></tr><tr><td>7</td><td>Reserved</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>DA</td><td>9:7</td><td>Dcache associativity:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Direct mapped</td></tr><tr><td>1</td><td>2-way</td></tr><tr><td>2</td><td>3-way</td></tr><tr><td>3</td><td>4-way</td></tr><tr><td>4</td><td>5-way</td></tr><tr><td>5</td><td>6-way</td></tr><tr><td>6</td><td>7-way</td></tr><tr><td>7</td><td>8-way</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>C2</td><td>6</td><td>Coprocessor 2 implemented:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No coprocessor 2 implemented</td></tr><tr><td>1</td><td>Coprocessor 2 implements</td></tr></table></td><td></td><td></td><td></td></tr>
<tr><td>MD</td><td>5</td><td>Used to denote MDMX ASE implemented on a MIPS64 processor. Not used on a MIPS32 processor.</td><td>R</td><td>0</td><td>Required</td></tr>
<tr><td>PC</td><td>4</td><td>Performance Counter registers implemented:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No performance counter registers implemented</td></tr><tr><td>1</td><td>Performance counter registers implemented</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>WR</td><td>3</td><td>Watch registers implemented:<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No watch registers implemented</td></tr><tr><td>1</td><td>Watch registers implemented</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
</table>

Table 6-21 Config1 Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>CA</td><td>2</td><td>Code compression (MIPS16) implemented:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>MIPS16 not implemented</td></tr><tr><td>1</td><td>MIPS16 implemented</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>EP</td><td>1</td><td>EJTAG implemented:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No EJTAG implemented</td></tr><tr><td>1</td><td>EJTAG implemented</td></tr></table></td><td>R</td><td>Preset</td><td>Required</td></tr>
<tr><td>FP</td><td>0</td><td>FPU implemented:
<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>No FPU implemented</td></tr><tr><td>1</td><td>FPU implemented</td></tr></table>If an FPU is implemented, the capabilities of the FPU can be read from the capability bits in the FIR CP1 register.</td><td>R</td><td>Preset</td><td>Required</td></tr>
</table>

6.21 Configuration Register 2 (CP0 Register 16, Select 2)

Compliance Level: *Optional.*

The *Config2* register encodes level 2 and level 3 cache configurations. The exact format of these fields is under review and will be resolved in the next release of this specification.

Figure 6-18 shows the format of the *Config2* register; Table 6-22 describes the *Config2* register fields.

Figure 6-18 Config2 Register Format

Table 6-22 Config2 Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	This bit is reserved to indicate that a Config3 register is present. If the Config3 register is not implemented, this bit should read as a 0. If the Config3 register is implemented, this bit should read as a 1.	R	Preset	Required
TBS	30..0	The specific definitions of the fields used to define the configuration of the level 2 and level 3 caches, will be specified in the future. Until those fields are defined, this field should read as zero and be ignored on writes.	R	Preset	Optional

6.22 Configuration Register 3 (CP0 Register 16, Select 3)

Compliance Level: *Optional.*

The *Config3* register encodes additional capabilities. All fields in the *Config3* register are read-only.

Figure 6-19 shows the format of the *Config3* register; Table 6-23 describes the *Config3* register fields.

Figure 6-19 Config3 Register Format

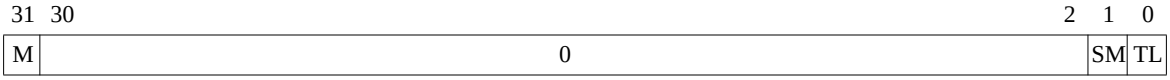


Table 6-23 Config3 Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	This bit is reserved to indicate that a Config4 register is present. With the current architectural definition, this bit should always read as a 0.	R	Preset	Required
0	30:2	Must be written as zeros; returns zeros on read	0	0	Reserved
SM	1	SmartMIPS™ ASE implemented. This bit indicates whether the SmartMIPS ASE is implemented. Encoding 0: SmartMIPS ASE is not implemented Encoding 1: SmartMIPS ASE is implemented	R	Preset	Optional
TL	0	Trace Logic implemented. This bit indicates whether PC or data trace is implemented. Encoding 0: Trace logic is not implemented Encoding 1: Trace logic is implemented	R	Preset	Optional

6.23 Reserved for Implementations (CP0 Register 16, Selects 6 and 7)

Compliance Level: *Optional: Implementation Dependent.*

CP0 register 16, Selects 6 and 7 are reserved for implementation dependent use and is not defined by the architecture. In order to use CP0 register 16, Selects 6 and 7, it is not necessary to implement CP0 register 16, Selects 2 through 5 only to set the M bit in each of these registers. That is, if the *Config2* and *Config3* registers are not needed for the implementation, they need not be implemented just to provide the M bits.

6.24 Load Linked Address (CP0 Register 17, Select 0)

Compliance Level: *Optional.*

The *LLAddr* register contains relevant bits of the physical address read by the most recent Load Linked instruction. This register is implementation dependent and for diagnostic purposes only and serves no function during normal operation.

Figure 6-20 shows the format of the *LLAddr* register; Table 6-24 describes the *LLAddr* register fields.

Figure 6-20 LLAddr Register Format

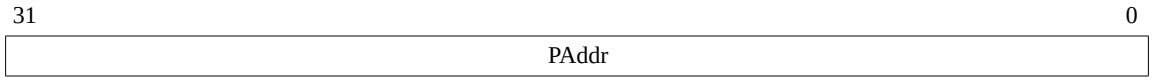


Table 6-24 LLAddr Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
PAddr	31..0	This field encodes the physical address read by the most recent Load Linked instruction. The format of this register is implementation dependent, and an implementation may implement as many of the bits or format the address in any way that it finds convenient.	R	Undefined	Optional

6.25 WatchLo Register (CP0 Register 18)

Compliance Level: *Optional.*

The *WatchLo* and *WatchHi* registers together provide the interface to a watchpoint debug facility which 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, the WP bit is set in the *Cause* register, and the watch exception is deferred until both the EXL and ERL bits are zero.

An implementation may provide zero or more pairs of WatchLo and WatchHi registers, referencing them via the select field of the MTC0/MFC0 instructions, and each pair of Watch registers may be dedicated to a particular type of reference (e.g., instruction or data). Software may determine if at least one pair of *WatchLo* and *WatchHi* registers are implemented via the WR bit of the *Config1* register. See the discussion of the M bit in the *WatchHi* register description below.

The *WatchLo* register specifies the base virtual address and the type of reference (instruction fetch, load, store) to match. If a particular Watch register only supports a subset of the reference types, the unimplemented enables must be ignored on write and return zero on read. Software may determine which enables are supported by a particular Watch register pair by setting all three enables bits and reading them back to see which ones were actually set.

It is implementation dependent whether a data watch is triggered by a prefetch or a cache instruction whose address matches the Watch register address match conditions.

Figure 6-21 shows the format of the *WatchLo* register; Table 6-25 describes the *WatchLo* register fields.

Figure 6-21 WatchLo Register Format

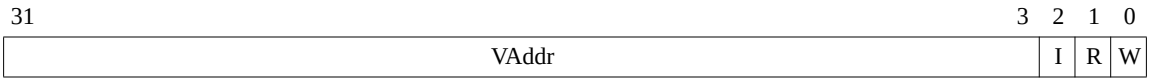


Table 6-25 WatchLo Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
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	Required
I	2	If this bit is one, watch exceptions are enabled for instruction fetches that match the address and are actually issued by the processor (speculative instructions never cause Watch exceptions). If this bit is not implemented, writes to it must be ignored, and reads must return zero.	R/W	0	Optional
R	1	If this bit is one, watch exceptions are enabled for loads that match the address. If this bit is not implemented, writes to it must be ignored, and reads must return zero.	R/W	0	Optional
W	0	If this bit is one, watch exceptions are enabled for stores that match the address. If this bit is not implemented, writes to it must be ignored, and reads must return zero.	R/W	0	Optional

6.26 WatchHi Register (CP0 Register 19)

Compliance Level: *Optional.*

The *WatchLo* and *WatchHi* registers together provide the interface to a watchpoint debug facility which 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, the WP bit is set in the *Cause* register, and the watch exception is deferred until both the EXL and ERL bits are zero.

An implementation may provide zero or more pairs of WatchLo and WatchHi registers, referencing them via the select field of the MTC0/MFC0 instructions, and each pair of Watch registers may be dedicated to a particular type of reference (e.g., instruction or data). Software may determine if at least one pair of *WatchLo* and *WatchHi* registers are implemented via the WR bit of the *Config1* register. If the M bit is one in the *WatchHi* register reference with a select field of '*n*', another WatchHi/WatchLo pair are implemented with a select field of '*n+1*'.

The *WatchHi* register contains information that qualifies the virtual address specified in the *WatchLo* register: an ASID, a G(lobal) bit, and an optional address mask. If the G bit is one, any virtual address reference that matches the specified address will cause a watch exception. If the G bit is a zero, 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*.

Figure 6-22 shows the format of the *WatchHi* register; Table 6-26 describes the *WatchHi* register fields.

Figure 6-22 WatchHi Register Format

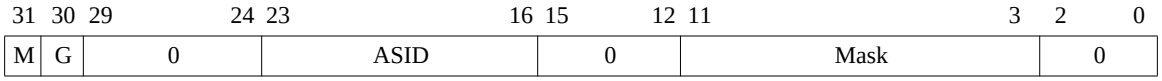


Table 6-26 WatchHi Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	If this bit is one, another pair of *WatchHi*/*WatchLo* registers is implemented at a MTC0 or MFC0 select field value of '*n+1*'	R	Preset	Required
G	30	If this bit is one, any address that matches that specified in the *WatchLo* register will cause a watch exception. If this bit is zero, the ASID field of the *WatchHi* register must match the ASID field of the *EntryHi* register to cause a watch exception.	R/W	Undefined	Required
ASID	23..16	ASID value which is required to match that in the *EntryHi* register if the G bit is zero in the *WatchHi* register.	R/W	Undefined	Required
Mask	11..3	Optional bit mask that qualifies the address in the *WatchLo* register. If this field is implemented, any bit in this field that is a one inhibits the corresponding address bit from participating in the address match. If this field is not implemented, writes to it must be ignored, and reads must return zero. Software may determine how many mask bits are implemented by writing ones the this field and then reading back the result.	R/W	Undefined	Optional

Table 6-26 WatchHi Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
0	29..24, 15..12, 2..0	Must be written as zero; returns zero on read.	0	0	Reserved

6.27 Reserved for Implementations (CP0 Register 22, all Select values)

Compliance Level: *Optional: Implementation Dependent.*

CP0 register 22 is reserved for implementation dependent use and is not defined by the architecture.

6.28 Debug Register (CP0 Register 23)

Compliance Level: *Optional*.

The *Debug* register is part of the EJTAG specification. Refer to that specification for the format and description of this register.

6.29 DEPC Register (CP0 Register 24)

Compliance Level: *Optional.*

The *DEPC* register is part of the EJTAG specification. Refer to that specification for the format and description of this register.

All bits of the *DEPC* register are significant and must be writable.

6.29.1 Special Handling of the DEPC Register in Processors That Implement the MIPS16 ASE

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

$$GPR[rt] \leftarrow RestartPC_{31..1} \,||\, ISAMode$$

That is, the upper 31 bits of the restart PC are combined with the *ISA Mode* bit 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 restart PC and the *ISA Mode* bit, as follows

$$RestartPC \leftarrow GPR[rt]_{31..1} \,||\, 0$$
$$ISAMode \leftarrow GPR[rt]_{0}$$

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the restart PC, and the lower bit of the restart PC is cleared. The *ISA Mode* bit is loaded from the lower bit of the GPR.

6.30 Performance Counter Register (CP0 Register 25)

Compliance Level: *Recommended.*

The MIPS32 Architecture supports implementation dependent performance counters that provide the capability to count events or cycles for use in performance analysis. If performance counters are implemented, each performance counter consists of a pair of registers: a 32-bit control register and a 32-bit counter register. To provide additional capability, multiple performance counters may be implemented.

Performance counters can be configured to count implementation dependent events or cycles under a specified set of conditions that are determined by the control register for the performance counter. The counter register increments once for each enabled event. When bit 31 of the counter register is a one (the counter overflows), the performance counter optionally requests an interrupt that is combined in an implementation dependent way with hardware interrupt 5 to set interrupt bit IP(7) in the *Cause* register. Counting continues after a counter register overflow whether or not an interrupt is requested or taken.

Each performance counter is mapped into even-odd select values of the *PerfCnt* register: Even selects access the control register and odd selects access the counter register. Table 6-27 shows an example of two performance counters and how they map into the select values of the *PerfCnt* register.

Table 6-27 Example Performance Counter Usage of the PerfCnt CP0 Register

Performance Counter	PerfCnt Register Select Value	PerfCnt Register Usage
0	PerfCnt, Select 0	Control Register 0
	PerfCnt, Select 1	Counter Register 0
1	PerfCnt, Select 2	Control Register 1
	PerfCnt, Select 3	Counter Register 1

More or less than two performance counters are also possible, extending the select field in the obvious way to obtain the desired number of performance counters. Software may determine if at least one pair of Performance Counter Control and Counter registers is implemented via the PC bit in the Config1 register. If the M bit is one in the Performance Counter Control register referenced via a select field of '*n*', another pair of Performance Counter Control and Counter registers is implemented at the select values of '*n+2*' and '*n+3*'.

The Control Register associated with each performance counter controls the behavior of the performance counter. Figure 6-23 shows the format of the Performance Counter Control Register; Table 6-28 describes the Performance Counter Control Register fields.

Figure 6-23 Performance Counter Control Register Format

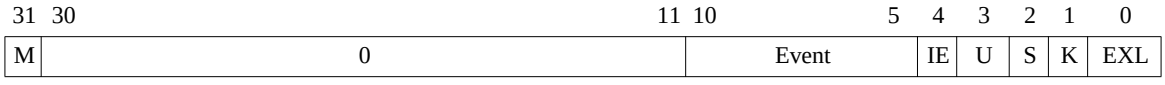


Table 6-28 Performance Counter Control Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
M	31	If this bit is a one, another pair of Performance Counter Control and Counter registers is implemented at a MTC0 or MFC0 select field value of '*n+2*' and '*n+3*'.	R	Preset	Required

Table 6-28 Performance Counter Control Register Field Descriptions

<table>
<tr><th colspan="2">Fields</th><th rowspan="2">Description</th><th rowspan="2">Read/ Write</th><th rowspan="2">Reset State</th><th rowspan="2">Compliance</th></tr>
<tr><th>Name</th><th>Bits</th></tr>
<tr><td>0</td><td>30..11</td><td>Must be written as zero; returns zero on read</td><td>0</td><td>0</td><td>Reserved</td></tr>
<tr><td>Event</td><td>10..5</td><td>Selects the event to be counted by the corresponding Counter Register. The list of events is implementation dependent, but typical events include cycles, instructions, memory reference instructions, branch instructions, cache and TLB misses, etc.

Implementations that support multiple performance counters allow ratios of events, e.g., cache miss ratios if cache miss and memory references are selected as the events in two counters</td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>IE</td><td>4</td><td>Interrupt Enable. Enables the interrupt request when the corresponding counter overflows (bit 31 of the counter is one).

Note that this bit simply enables the interrupt request. The actual interrupt is still gated by the normal interrupt masks and enable in the Status register.

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Performance counter interrupt disabled</td></tr><tr><td>1</td><td>Performance counter interrupt enabled</td></tr></table></td><td>R/W</td><td>0</td><td>Required</td></tr>
<tr><td>U</td><td>3</td><td>Enables event counting in User Mode. Refer to Section 3.4 on page 9 for the conditions under which the processor is operating in User Mode.

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Disable event counting in User Mode</td></tr><tr><td>1</td><td>Enable event counting in User Mode</td></tr></table></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>S</td><td>2</td><td>Enables event counting in Supervisor Mode (for those processors that implement Supervisor Mode). Refer to Section 3.3 on page 9 for the conditions under which the processor is operating in Supervisor mode.

If the processor does not implement Supervisor Mode, this bit must be ignored on write and return zero on read.

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Disable event counting in Supervisor Mode</td></tr><tr><td>1</td><td>Enable event counting in Supervisor Mode</td></tr></table></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
<tr><td>K</td><td>1</td><td>Enables event counting in Kernel Mode. Unlike the usual definition of Kernel Mode as described in Section 3.2 on page 9, this bit enables event counting only when the EXL and ERL bits in the Status register are zero.

<table><tr><th>Encoding</th><th>Meaning</th></tr><tr><td>0</td><td>Disable event counting in Kernel Mode</td></tr><tr><td>1</td><td>Enable event counting in Kernel Mode</td></tr></table></td><td>R/W</td><td>Undefined</td><td>Required</td></tr>
</table>

Table 6-28 Performance Counter Control Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
EXL	0	Enables event counting when the EXL bit in the *Status* register is one and the ERL bit in the *Status* register is zero. Encoding / Meaning: 0 — Disable event counting while EXL = 1, ERL = 0 1 — Enable event counting while EXL = 1, ERL = 0 Counting is never enabled when the ERL bit in the *Status* register or the DM bit in the *Debug* register is one.	R/W	Undefined	Required

The Counter Register associated with each performance counter increments once for each enabled event. Figure 6-24 shows the format of the Performance Counter Counter Register; Table 6-29 describes the Performance Counter Counter Register fields.

Figure 6-24 Performance Counter Counter Register Format

Table 6-29 Performance Counter Counter Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
Event Count	31..0	Increments once for each event that is enabled by the corresponding Control Register. When bit 31 is one, an interrupt request is made if the IE bit in the Control Register is one.	R/W	Undefined	Required

6.31 ErrCtl Register (CP0 Register 26, Select 0)

Compliance Level: *Optional.*

The *ErrCtl* register provides an implementation dependent diagnostic interface with the error detection mechanisms implemented by the processor. This register has been used in previous implementations to read and write parity or ECC information to and from the primary or secondary cache data arrays in conjunction with specific encodings of the Cache instruction or other implementation-dependent method. The exact format of the ErrCtl register is implementation dependent and not specified by the architecture. Refer to the processor specification for the format of this register and a description of the fields.

6.32 CacheErr Register (CP0 Register 27, Select 0)

Compliance Level: *Optional.*

The CacheErr register provides an interface with the cache error detection logic that may be implemented by a processor.

The exact format of the *CacheErr* register is implementation dependent and not specified by the architecture. Refer to the processor specification for the format of this register and a description of the fields.

6.33 TagLo Register (CP0 Register 28, Select 0, 2)

Compliance Level: *Required* if a cache is implemented*; Optional* otherwise.

The *TagLo* and *TagHi* registers are read/write registers that act as the interface to the cache tag array. The Index Store Tag and Index Load Tag operations of the CACHE instruction use the *TagLo* and *TagHi* registers as the source or sink of tag information, respectively.

The exact format of the *TagLo* and *TagHi* registers is implementation dependent. Refer to the processor specification for the format of this register and a description of the fields.

However, software must be able to write zeros into the *TagLo* and *TagHi* registers and then use the Index Store Tag cache operation to initialize the cache tags to a valid state at powerup.

It is implementation dependent whether there is a single *TagLo* register that acts as the interface to all caches, or a dedicated *TagLo* register for each cache. If multiple *TagLo* registers are implemented, they occupy the even select values for this register encoding, with select 0 addressing the instruction cache and select 2 addressing the data cache. Whether individual *TagLo* registers are implemented or not for each cache, processors must accept a write of zero to select 0 and select 2 of *TagLo* as part of the software process of initializing the cache tags at powerup.

6.34 DataLo Register (CP0 Register 28, Select 1, 3)

Compliance Level: *Optional.*

The *DataLo* and *DataHi* registers are read-only registers that act as the interface to the cache data array and are intended for diagnostic operation only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *DataLo* and *DataHi* registers.

The exact format and operation of the *DataLo* and *DataHi* registers is implementation dependent. Refer to the processor specification for the format of this register and a description of the fields.

It is implementation dependent whether there is a single *DataLo* register that acts as the interface to all caches, or a dedicated *DataLo* register for each cache. If multiple *DataLo* registers are implemented, they occupy the odd select values for this register encoding, with select 1 addressing the instruction cache and select 3 addressing the data cache.

6.35 TagHi Register (CP0 Register 29, Select 0, 2)

Compliance Level: *Required* if a cache is implemented*; Optional* otherwise.

The *TagLo* and *TagHi* registers are read/write registers that act as the interface to the cache tag array. The Index Store Tag and Index Load Tag operations of the CACHE instruction use the *TagLo* and *TagHi* registers as the source or sink of tag information, respectively.

The exact format of the *TagLo* and *TagHi* registers is implementation dependent. Refer to the processor specification for the format of this register and a description of the fields. However, software must be able to write zeros into the *TagLo* and *TagHi* registers and the use the Index Store Tag cache operation to initialize the cache tags to a valid state at powerup.

It is implementation dependent whether there is a single *TagHi* register that acts as the interface to all caches, or a dedicated *TagHi* register for each cache. If multiple *TagHi* registers are implemented, they occupy the even select values for this register encoding, with select 0 addressing the instruction cache and select 2 addressing the data cache. Whether individual *TagHi* registers are implemented or not for each cache, processors must accept a write of zero to select 0 and select 2 of *TagHi* as part of the software process of initializing the cache tags at powerup.

6.36 DataHi Register (CP0 Register 29, Select 1, 3)

Compliance Level: *Optional.*

The *DataLo* and *DataHi* registers are read-only registers that act as the interface to the cache data array and are intended for diagnostic operation only. The Index Load Tag operation of the CACHE instruction reads the corresponding data values into the *DataLo* and *DataHi* registers.

The exact format and operation of the *DataLo* and *DataHi* registers is implementation dependent. Refer to the processor specification for the format of this register and a description of the fields.

6.37 ErrorEPC (CP0 Register 30, Select 0)

Compliance Level: *Required.*

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, Nonmaskable Interrupt (NMI), and Cache Error exceptions.

The *ErrorEPC* register contains the virtual address at which instruction processing can resume after servicing an error. *ErrorEPC* contains either:

- the virtual address of the instruction that was the direct cause of 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.

Figure 6-25 shows the format of the *ErrorEPC* register; Table 6-30 describes the *ErrorEPC* register fields.

Figure 6-25 ErrorEPC Register Format

Table 6-30 ErrorEPC Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
ErrorEPC	31..0	Error Exception Program Counter	R/W	Undefined	Required

6.37.1 Special Handling of the ErrorEPC Register in Processors That Implement the MIPS16 ASE

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

```
GPR[rt] ← RestartPC31..1 || ISAMode
```

That is, the upper 31 bits of the restart PC are combined with the *ISA Mode* bit 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 restart PC and the *ISA Mode* bit, as follows

```
RestartPC ← GPR[rt]31..1 || 0
ISAMode ← GPR[rt]0
```

That is, the upper 31 bits of the GPR are written to the upper 31 bits of the restart PC, and the lower bit of the restart PC is cleared. The *ISA Mode* bit is loaded from the lower bit of the GPR.

6.38 DESAVE Register (CP0 Register 31)

Compliance Level: *Optional*.

The *DESAVE* register is part of the EJTAG specification. Refer to that specification for the format and description of this register.

CP0 Hazards

7.1 Introduction

Because resources controlled via Coprocessor 0 affect the operation of various pipeline stages of a MIPS32 processor, manipulation of these resources may produce results that are not detectable by subsequent instructions for some number of execution cycles. When no hardware interlock exists between one instruction that causes an effect that is visible to a second instruction, a *CP0 hazard* exists. Some MIPS implementations have placed the entire burden on the kernel programmer to pad the instruction stream in such a way that the second instruction is spaced far enough from the first that the effects of the first are seen by the second. Other MIPS implementations have added full hardware interlocks such that the kernel programmer need not pad. The trade-off is between kernel software changes for each new processor vs. more complex hardware interlocks required in the processor.

The MIPS32 Architecture does not dictate the solution that is required for a compatible implementation. The choice of implementation ranges from full hardware interlocks to full dependence on software padding, to some combination of the two. For an implementation choice that relies on software padding, Table 7-1 lists the "typical" spacing required to allow the consumer to eliminate the hazard. The "typical" values shown in this table represent spacing that is in common use by operating systems today. An implementation which requires less spacing to clear the hazard (including one which has full hardware interlocking) should operate correctly with and operating system which uses this hazard table. An implementation which requires more spacing to clear the hazard incurs the burden of validating kernel code against the new hazard requirements.

Note that, for superscalar MIPS implementations, the number of instructions issued per cycle may be greater than one, and thus that the duration of the hazard in instructions may be greater than the duration in cycles. It is for this reason that MIPS32 defines the SSNOP instruction to convert instruction issues to cycles in a superscalar design.

Table 7-1 "Typical" CP0 Hazard Spacing

Producer	→	Consumer	Hazard On	"Typical" Spacing (Cycles)
TLBWR, TLBWI	→	TLBP, TLBR	TLB entry	3
		Load/store using new TLB entry	TLB entry	3
		Instruction fetch using new TLB entry	TLB entry	5
MTCO Status[CU]	→	Coprocessor instruction needs CU set	Status[CU]	4
MTC0 Status	→	ERET	Status	3
MTC0 Status[IE]	→	Interrupted Instruction	Status[IE]	3
TLBR	→	MFC0 EntryHi MFC0 PageMask	EntryHi, PageMask	3
MTC0 EntryLo0 MTC0 EntryLo1 MTC0 Entry Hi MTC0 PageMask MTC0 Index	→	TLBP TLBR TLBWI TLBWR	EntryLo0 EntryLo1 EntryHi PageMask Index	2

Producer	→	Consumer	Hazard On	"Typical" Spacing (Cycles)
TLBP	→	MFC0 Index	Index	2
MTC0 EPC	→	ERET	EPC	2

Alternative MMU Organizations

The main body of this specification describes the TLB-based MMU organization. This appendix describes other potential MMU organizations.

A.1 Fixed Mapping MMU

As an alternative to the full TLB-based MMU, the MIPS32 Architecture supports a lightweight memory management mechanism with fixed virtual-to-physical address translation, and no memory protection beyond what is provided by the address error checks required of all MMUs. This may be useful for those applications which do not require the capabilities of a full TLB-based MMU.

A.1.1 Fixed Address Translation

Address translation using the Fixed Mapping MMU is done as follows:

- Kseg0 and Kseg1 addresses are translated in an identical manner to the TLB-based MMU: they both map to the low 512MB of physical memory.
- Useg/Suseg/Kuseg addresses are mapped by adding 1GB to the virtual address when the ERL bit is zero in the Status register, and are mapped using an identity mapping when the ERL bit is one in the Status register.
- Sseg/Ksseg/Kseg2/Kseg3 addresses are mapped using an identity mapping.

Table 7-2 lists all mappings from virtual to physical addresses. Note that address error checking is still done before the translation process. Therefore, an attempt to reference kseg0 from User Mode still results in an address error exception, just as it does with a TLB-based MMU.

Table 7-2 Physical Address Generation from Virtual Addresses

Segment Name	Virtual Address	Generates Physical Address	
		$Status_{ERL}$ = 0	$Status_{ERL}$ = 1
useg suseg kuseg	16#0000 0000 through 16#7FFF FFFF	16#4000 0000 through 16#BFFF FFFF	16#0000 0000 through 16#7FFF FFFF
kseg0	16#8000 0000 through 16#9FFF FFFF	16#0000 0000 through 16#1FFF FFFF	
kseg1	16#A000 0000 through 16#BFFF FFFF	16#0000 0000 through 16#16#1FFF FFFF	
sseg ksseg kseg2	16#C000 0000 through 16#DFFF FFFF	16#C000 0000 through 16#DFFF FFFF	

Table 7-2 Physical Address Generation from Virtual Addresses

Segment Name	Virtual Address	Generates Physical Address	
		$Status_{ERL}$ = 0	$Status_{ERL}$ = 1
kseg3	16#E000 0000 through 16#FFFF FFFF	16#E000 0000 through 16#FFFF FFFF	

Note that this mapping means that physical addresses 16#2000 0000 through 16#3FFF FFFF are inaccessible when the ERL bit is off in the *Status* register, and physical addresses 16#8000 0000 through 16#BFFF FFFF are inaccessible when the ERL bit is on in the *Status* register.

Figure 7-1 shows the memory mapping when the ERL bit in the *Status* register is zero; Figure 7-2 shows the memory mapping when the ERL bit is one.

Figure 7-1 Memory Mapping when ERL = 0

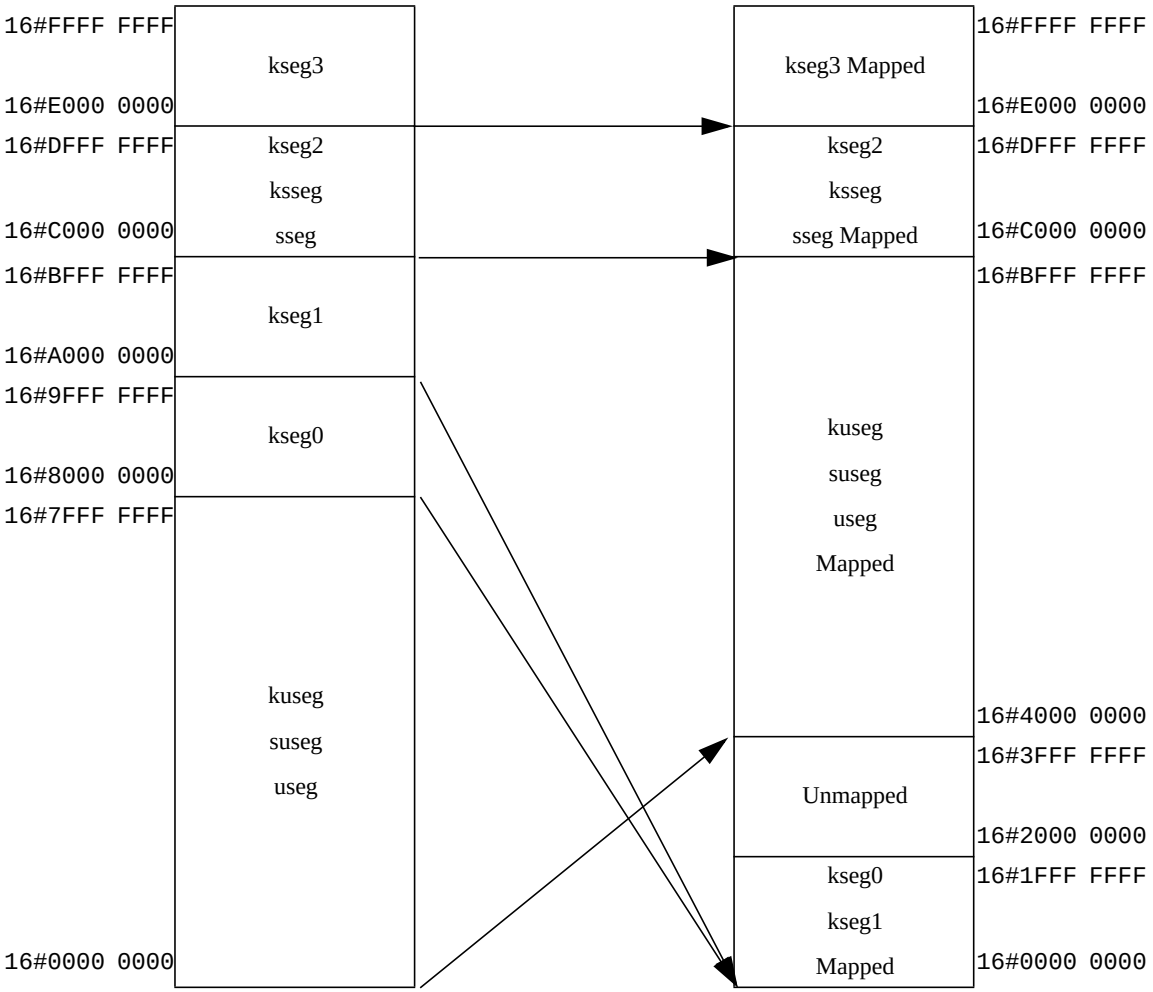
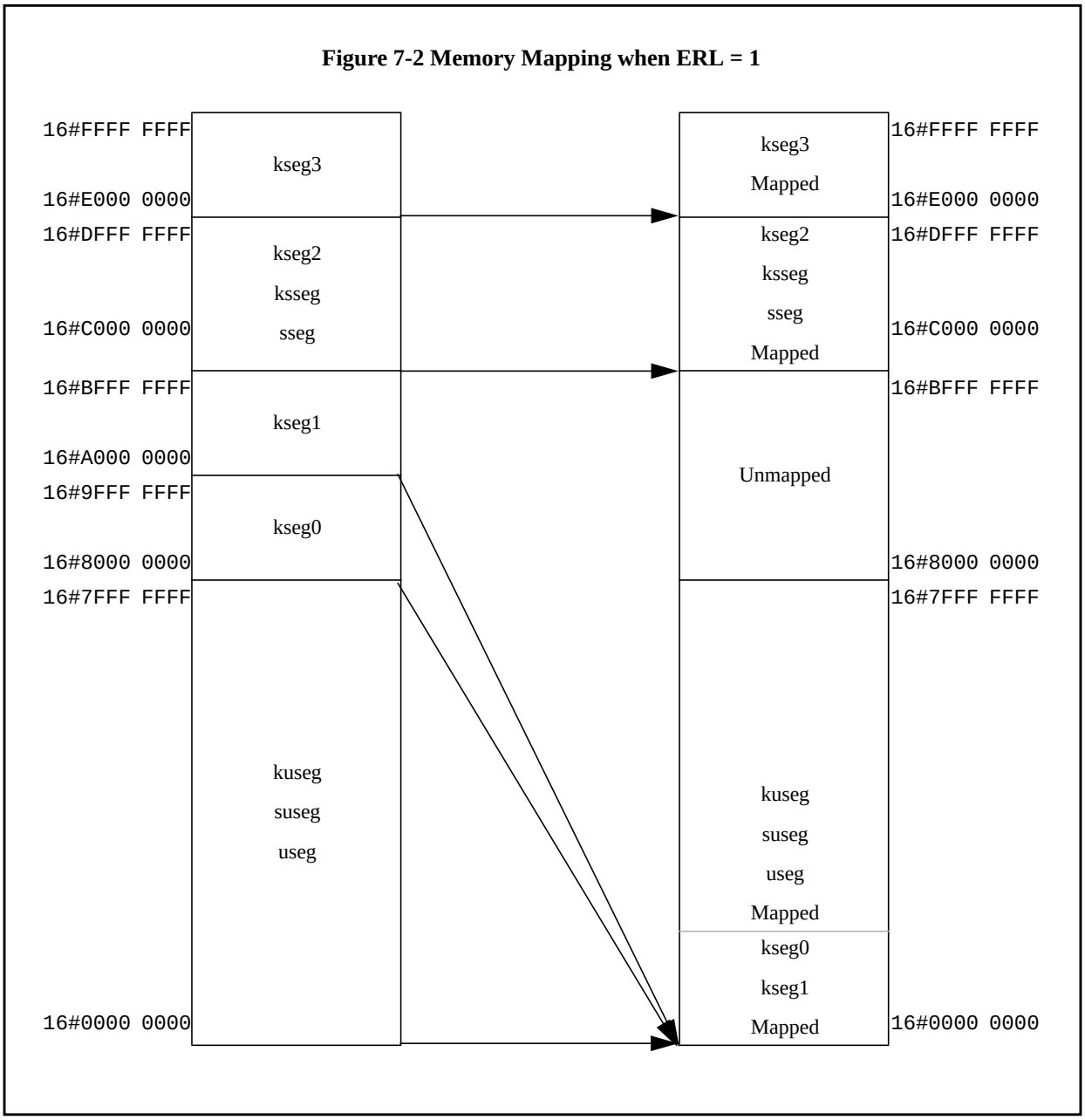


Figure 7-2 Memory Mapping when ERL = 1



A.1.2 Cacheability Attributes

Because the TLB provided the cacheability attributes for the kuseg, kseg2, and kseg3 segments, some mechanism is required to replace this capability when the fixed mapping MMU is used. Two additional fields are added to the *Config* register whose encoding is identical to that of the K0 field. These additions are the K23 and KU fields which control the cacheability of the kseg2/kseg3 and the kuseg segments, respectively. Note that when the ERL bit is on in the Status register, kuseg references are always treated as uncacheable references, independent of the value of the KU field.

The cacheability attributes for kseg0 and kseg1 are provided in the same manner as for a TLB-based MMU: the cacheability attribute for kseg0 comes from the K0 field of *Config*, and references to kseg1 are always uncached.

Figure 7-3 shows the format of the additions to the *Config* register; Table 7-3 describes the new *Config* register fields.

Figure 7-3 Config Register Additions

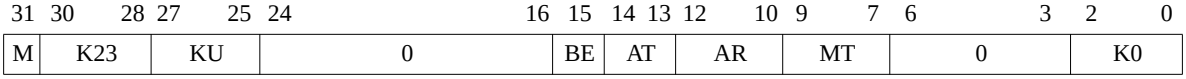


Table 7-3 Config Register Field Descriptions

Fields		Description	Read/ Write	Reset State	Compliance
Name	Bits				
K23	30:28	Kseg2/Kseg3 coherency algorithm. See Table 6-6 on page 44 for the encoding of this field.	R/W	Undefined	Optional
KU	27:25	Kuseg coherency algorithm when $Status_{ERL}$ is zero. See Table 6-6 on page 44 for the encoding of this field.	R/W	Undefined	Optional

A.1.3 Changes to the CP0 Register Interface

Relative to the TLB-based address translation mechanism, the following changes are necessary to the CP0 register interface:

- The Index, Random, EntryLo0, EntryLo1, Context, PageMask, Wired, and EntryHi registers are no longer required and may be removed.
- The TLBWR, TLBWI, TLBP, and TLBR instructions are no longer required and should cause a Reserved Instruction Exception.

A.2 Block Address Translation

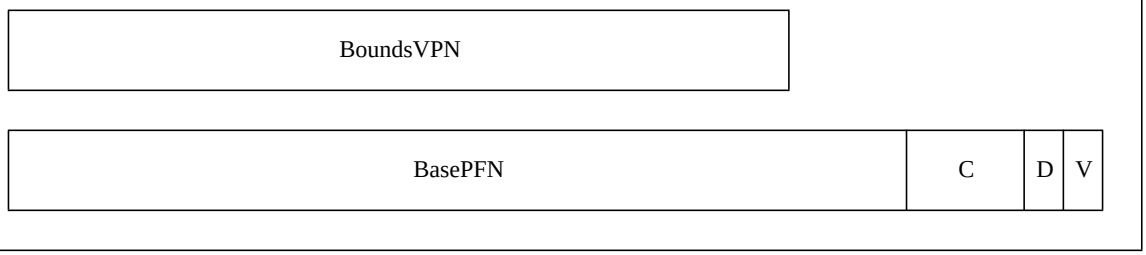
This section describes the architecture for a block address translation (BAT) mechanism that reuses much of the hardware and software interface that exists for a TLB-Based virtual address translation mechanism. This mechanism has the following features:

- It preserves as much as possible of the TLB-Based interface, both in hardware and software.
- It provides independent base-and-bounds checking and relocation for instruction references and data references.
- It provides optional support for base-and-bounds relocation of kseg2 and kseg3 virtual address regions.

A.2.1 BAT Organization

The BAT is an indexed structure which is used to translate virtual addresses. It contains pairs of instruction/data entries which provide the base-and-bounds checking and relocation for instruction references and data references, respectively. Each entry contains a page-aligned bounds virtual page number, a base page frame number (whose width is implementation dependent), a cache coherence field (C), a dirty (D) bit, and a valid (V) bit. Figure 7-4 shows the logical arrangement of a BAT entry.

Figure 7-4 Contents of a BAT Entry



The BAT is indexed by the reference type and the address region to be checked as shown in Table 7-4.

Table 7-4 BAT Entry Assignments

Entry Index	Reference Type	Address Region
0	Instruction	useg/kuseg
1	Data	
2	Instruction	kseg2 (or kseg2 and kseg3)
3	Data	
4	Instruction	kseg3
5	Data	

Entries 0 and 1 are required. Entries 2, 3, 4 and 5 are optional and may be implemented as necessary to address the needs of the particular implementation. If entries for kseg2 and kseg3 are not implemented, it is implementation-dependent how, if at all, these address regions are translated. One alternative is to combine the mapping for kseg2 and kseg3 into a single pair of instruction/data entries. Software may determine how many BAT entries are implemented by looking at the MMU Size field of the *Config1* register.

A.2.2 Address Translation

When a virtual address translation is requested, the BAT entry that is appropriate to the reference type and address region is read. If the virtual address is greater than the selected bounds address, or if the valid bit is off in the entry, a TLB Invalid exception of the appropriate reference type is initiated. If the reference is a store and the D bit is off in the entry, a TLB Modified exception is initiated. Otherwise, the base PFN from the selected entry, shifted to align with bit 12, is added to the virtual address to form the physical address. The BAT process can be described as follows:

```
i ← SelectIndex (reftype, va)
bounds ← BAT[i]BoundsVPN || 1^12
pfn ← BAT[i]BasePFN
c ← BAT[i]C
d ← BAT[i]D
v ← BAT[i]V
if (va > bounds) or (v = 0) then
   InitiateTLBInvalidException(reftype)
endif
if (d = 0) and (reftype = store) then
   InitiateTLBModifiedException()
endif
pa ← va + (pfn || 0^12)
```

Making all addresses out-of-bounds can only be done by clearing the valid bit in the BAT entry. Setting the bounds value to zero leaves the first virtual page mapped.

A.2.3 Changes to the CP0 Register Interface

Relative to the TLB-based address translation mechanism, the following changes are necessary to the CP0 register interface:

- The *Index* register is used to index the BAT entry to be read or written by the TLBWI and TLBR instructions.
- The *EntryHi* register is the interface to the BoundsVPN field in the BAT entry.
- The *EntryLo0* register is the interface to the BasePFN and C, D, and V fields of the BAT entry. The register has the same format as for a TLB-based MMU.
- The *Random*, *EntryLo1*, *Context*, *PageMask*, and *Wired* registers are eliminated. The effects of a read or write to these registers is **UNDEFINED**.
- The TLBP and TLBWR instructions are unnecessary. The TLBWI and TLBR instructions reference the BAT entry whose index is contained in the *Index* register. The effects of executing a TLBP or TLBWR are **UNDEFINED**, but processors should prefer a Reserved Instruction Exception.

Revision History

Revision	Date	Description
0.92	January 20, 2001	Internal review copy of reorganized and updated architecture documentation.
0.95	March 12, 2001	Clean up document for external review release