Table of Contents

Preface

Overview of the Contents vii
A Note on Style ix

Preface to the Second Edition

Changes From the First Edition xi
Getting MIPS Documents On-Line xi

1 Introduction

Benefits of RISC Design 2
Shorter Design Cycle 3
Effective Utilization of Chip Area 3
User (Programmer) Benefits 3
Advanced Semiconductor Technologies 3
Optimizing Compilers 4
MIPS RISCompiler Language Suite 5
Compatibility 6
Processor General Features 6
R4000 Processor Configurations 7
R4400 Processor Enhancements 7
R4000 Processor 9
64-bit Architecture 9
Superpipeline Architecture 11
System Interface 11
CPU Register Overview 12
CPU Instruction Set Overview 14
Data Formats and Addressing 24
Coprocessors (CP0-CP2) 27
System Control Coprocessor, CP0 27
Floating-Point Unit (FPU), CP1 30
Memory Management System (MMU) 31
The Translation Lookaside Buffer (TLB) 31
Operating Modes 32
Cache Memory Hierarchy 32
Primary Caches 33
Secondary Cache Interface 33

2 CPU Instruction Set Summary

CPU Instruction Formats 36
Load and Store Instructions 37
Scheduling a Load Delay Slot 37
Defining Access Types 37
Computational Instructions 39
64-bit Operations 39
Cycle Timing for Multiply and Divide Instructions 40
Jump and Branch Instructions 41
Overview of Jump Instructions 41
Overview of Branch Instructions 41
Special Instructions 42
Exception Instructions 42
Coprocessor Instructions 42

3 The CPU Pipeline

CPU Pipeline Operation 44
CPU Pipeline Stages 45
Branch Delay 48
Load Delay 48
Interlock and Exception Handling 49
Exception Conditions 52
Stall Conditions 53
Slip Conditions 53
External Stalls 53
Interlock and Exception Timing 53
Backing Up the Pipeline 54
Aborting an Instruction Subsequent to an Interlock 55
Pipelining the Exception Handling 56
Special Cases 58
Performance Considerations 58
Correctness Considerations 58
R4400 Processor Uncached Store Buffer 59

4
Memory Management

Translation Lookaside Buffer (TLB) 62
Hits and Misses 62
Multiple Matches 62
Address Spaces 63
Virtual Address Space 63
Physical Address Space 64
Virtual-to-Physical Address Translation 64
32-bit Mode Address Translation 65
64-bit Mode Address Translation 66
Operating Modes 67
User Mode Operations 67
Supervisor Mode Operations 69
Kernel Mode Operations 73
System Control Coprocessor 80
Format of a TLB Entry 81
CP0 Registers 84
Index Register (0) 85
Random Register (1) 86
EntryLo0 (2), and EntryLo1 (3) Registers 87
PageMask Register (5) 87
Wired Register (6) 88
EntryHi Register (CP0 Register 10) 89
Processor Revision Identifier (PRId) Register (15) 89
Config Register (16) 90
Load Linked Address (LLAddr) Register (17) 93
Cache Tag Registers [TagLo (28) and TagHi (29)] 93
Virtual-to-Physical Address Translation Process 95
TLB Misses 97
TLB Instructions 97

5 CPU Exception Processing

How Exception Processing Works 100
Exception Processing Registers 101
Context Register (4) 102
Bad Virtual Address Register (BadVAddr) (8) 103
Count Register (9) 103
Compare Register (11) 104
Status Register (12) 105
Status Register Format 105
Status Register Modes and Access States 109
Status Register Reset 110
Cause Register (13) 110
Exception Program Counter (EPC) Register (14) 112
WatchLo (18) and WatchHi (19) Registers 113
XContext Register (20) 114
Error Checking and Correcting (ECC) Register (26) 115
Cache Error (CacheErr) Register (27) 116
Error Exception Program Counter (Error EPC) Register (30) 118
Processor Exceptions 119
Exception Types 119
Reset Exception Process 120
Cache Error Exception Process 120
Soft Reset and NMI Exception Process 121
General Exception Process 121
Exception Vector Locations 122
Priority of Exceptions 123
Reset Exception 124
Soft Reset Exception 125
Address Error Exception 127
TLB Exceptions 128
TLB Refill Exception 129
TLB Invalid Exception 130
TLB Modified Exception 131
Cache Error Exception 132
Virtual Coherency Exception 133
Bus Error Exception 134
Integer Overflow Exception 135

Trap Exception 136
System Call Exception 137
Breakpoint Exception 138
Reserved Instruction Exception 139
Coprocessor Unusable Exception 140
Floating-Point Exception 141
Watch Exception 142
Interrupt Exception 143
Exception Handling and Servicing Flowcharts 144

6 Floating-Point Unit

Overview 152
FPU Features 153
FPU Programming Model 154
Floating-Point General Registers (FGRs) 154
Floating-Point Registers 156
Floating-Point Control Registers 157
Implementation and Revision Register, (FCR0) 158
Control/Status Register (FCR31) 159
Accessing the Control/Status Register 160
IEEE Standard 754 161
Control/Status Register FS Bit 161
Control/Status Register Condition Bit 161
Control/Status Register Cause, Flag, and Enable Fields 161
Control/Status Register Rounding Mode Control Bits 163
Floating-Point Formats 164
Binary Fixed-Point Format 166
Floating-Point Instruction Set Overview 167
Floating-Point Load, Store, and Move Instructions 169
Transfers Between FPU and Memory 169
Transfers Between FPU and CPU 169
Load Delay and Hardware Interlocks 169
Data Alignment 170
Endianness 170
Floating-Point Conversion Instructions 170
Floating-Point Computational Instructions 170
Branch on FPU Condition Instructions 170
Floating-Point Compare Operations 171
FPU Instruction Pipeline Overview 172
Instruction Execution 172
Instruction Execution Cycle Time 173
Scheduling FPU Instructions 175
FPU Pipeline Overlapping 175
Instruction Scheduling Constraints 176
Instruction Latency, Repeat Rate, and Pipeline Stage Sequences 181
Resource Scheduling Rules 182

7 Floating-Point Exceptions

Exception Types 188
Exception Trap Processing 189
Flags 190
FPU Exceptions 192
Inexact Exception (I) 192
Invalid Operation Exception (V) 193
Division-by-Zero Exception (Z) 194
Overflow Exception (O) 194
Underflow Exception (U) 195
Unimplemented Instruction Exception (E) 196
Saving and Restoring State 197
Trap Handlers for IEEE Standard 754 Exceptions 198

8 R4000 Processor Signal Descriptions

System Interface Signals 201
Clock/Control Interface Signals 203
Secondary Cache Interface Signals 205
Interrupt Interface Signals 207
JTAG Interface Signals 207
Initialization Interface Signals 208
Signal Summary 209

9 Initialization Interface

Functional Overview 214
Reset Signal Description 215
Power-on Reset 216
Cold Reset 217
Warm Reset 217
Initialization Sequence 218
Boot-Mode Settings 222

10 Clock Interface

Signal Terminology 228
Basic System Clocks 229
MasterClock 229
MasterOut 229
SyncIn/SyncOut 229
PClock 229
SClock 230
TClock 230
RClock 230
PClock-to-SClock Division 230
System Timing Parameters 233
Alignment to SClock 233
Alignment to MasterClock 233
Phase-Locked Loop (PLL) 233
Connecting Clocks to a Phase-Locked System 234
Connecting Clocks to a System without Phase Locking 235
Connecting to a Gate-Array Device 235
Connecting to a CMOS Logic System 238
Processor Status Outputs 241

11
Cache Organization, Operation, and Coherency

Memory Organization 244
Overview of Cache Operations 245
R4000 Cache Description 246
Secondary Cache Size 248
Variable-Length Cache Lines 248
Cache Organization and Accessibility 248
Organization of the Primary Instruction Cache (I-Cache) 249
Organization of the Primary Data Cache (D-Cache) 250
Accessing the Primary Caches 251
Organization of the Secondary Cache 252
Accessing the Secondary Cache 254
Cache States 255
Primary Cache States 256
Secondary Cache States 256
Mapping States Between Caches 257
Cache Line Ownership 258
Cache Write Policy 259
Cache State Transition Diagrams 260
Cache Coherency Overview 264
Cache Coherency Attributes 264
Uncached 265
Noncoherent 265
Sharable 265
Update 265
Exclusive 266
Cache Operation Modes 266
Secondary-Cache Mode 266
No-Secondary-Cache Mode 266
Strong Ordering 267
An Example of Strong Ordering 267
Testing for Strong Ordering 267
Restarting the Processor 268
Maintaining Coherency on Loads and Stores 269
Manipulation of the Cache by an External Agent 270
Invalidate 270
Update 270

Snoop 270
Intervention 271
Coherency Conflicts 271
How Coherency Conflicts Arise 272
Processor Coherent Read Requests 272
Processor Invalidate or Update Requests 273
External Coherency Requests 274
System Implications of Coherency Conflicts 275
System Model 276
Load 278
Store 278
Processor Coherent Read Request and Read Response 278
Processor Invalidate 279
Processor Write 279
Handling Coherency Conflicts 280
Coherent Read Conflicts 280
Coherent Write Conflicts 281
Invalidate Conflicts 282
Sample Cycle: Coherent Read Request 283
R4000 Processor Synchronization Support 286
Test-and-Set (Spinlock) 286
Counter 288
LL and SC 289
Examples Using LL and SC 290

12 System Interface

Terminology 294
System Interface Description 294
Interface Buses 295
Address and Data Cycles 296
Issue Cycles 296
Handshake Signals 298
System Interface Protocols 299
Master and Slave States 299
Moving from Master to Slave State 300
External Arbitration 300
Uncompelled Change to Slave State 301
Processor and External Requests 302
Rules for Processor Requests 303
Processor Requests 304
Processor Read Request 306
Processor Write Request 307
Processor Invalidate Request 308
Processor Update Request 310
Clusters 311
External Requests 313
External Read Request 316
External Write Request 316
External Invalidate Request 316
External Update Request 316
External Snoop Request 317
External Intervention Request 317
Read Response 317
Handling Requests 318
Load Miss 318
Secondary-Cache Mode 320
No-Secondary-Cache Mode 320
Store Miss 321
Secondary-Cache Mode 323
No-Secondary-Cache Mode 325
Store Hit 326
Secondary-Cache Mode 326

No-Secondary-Cache Mode 326
Uncached Loads or Stores 326
CACHE Operations 327
Load Linked Store Conditional Operation 327
Processor and External Request Protocols 329
Processor Request Protocols 330
Processor Read Request Protocol 330
Processor Write Request Protocol 333
Processor Invalidate and Update Request Protocol 335
Processor Null Write Request Protocol 336
Processor Cluster Request Protocol 337
Processor Request and Cluster Flow Control 338
External Request Protocols 341
External Arbitration Protocol 342
External Read Request Protocol 343
External Null Request Protocol 344
External Write Request Protocol 347
External Invalidate and Update Request Protocols 348
External Intervention Request Protocol 349
External Snoop Request Protocol 352
Read Response Protocol 354
Data Rate Control 356
Data Transfer Patterns 356
Secondary Cache Transfers 357
Secondary Cache Write Cycle Time 358
Independent Transmissions on the SysAD Bus 359
System Interface Endianness 360
System Interface Cycle Time 361
Cluster Request Spacing 361
Release Latency 362
External Request Response Latency 363
System Interface Commands and Data Identifiers 364
Command and Data Identifier Syntax 364
System Interface Command Syntax 365
Read Requests 366
Write Requests 367
Null Requests 369
Invalidate Requests 370

Update Requests 370
Intervention and Snoop Requests 372
System Interface Data Identifier Syntax 374
Coherent Data 374
Noncoherent Data 374
Data Identifier Bit Definitions 375
System Interface Addresses 377
Addressing Conventions 377
Sequential and Subblock Ordering 378
Processor Internal Address Map 378

13
Secondary Cache Interface

Data Transfer Rates 380
Duplicating Signals 380
Accessing a Split Secondary Cache 381
SCDChk Bus 381
SCTAG Bus 381
Operation of the Secondary Cache Interface 382
Read Cycles 383
4-Word Read Cycle 383
8-Word Read Cycle 384
Notes on a Secondary Cache Read Cycle 384
Write Cycles 385
4-Word Write Cycle 385
8-Word Write Cycle 386
Notes on a Secondary Cache Write Cycle 387

14 JTAG Interface

What Boundary Scanning Is 390
Signal Summary 391
JTAG Controller and Registers 392
Instruction Register 392
Bypass Register 393
Boundary-Scan Register 394
Test Access Port (TAP) 395
TAP Controller 396
Controller Reset 396
Controller States 396
Implementation-Specific Details 400

15 R4000 Processor Interrupts

Hardware Interrupts 402
Nonmaskable Interrupt (NMI) 402
Asserting Interrupts 402

16 Error Checking and Correcting

Error Checking in the Processor 408
Types of Error Checking 408
Parity Error Detection 408
SECDED ECC Code 409
Error Checking Operation 412
System Interface 412
Secondary Cache Data Bus 412
System Interface and Secondary Cache Data Bus 412
Secondary Cache Tag Bus 413
System Interface Command Bus 413
SECDED ECC Matrices for Data and Tag Buses 414
ECC Check Bits 414
Data ECC Generation 415
Detecting Data Transmission Errors 418
Single Data Bit ECC Error 420
Single Check Bit ECC Error 421
Double Data Bit ECC Errors 422
Three Data Bit ECC Errors 423
Four Data Bit ECC Errors 424
Tag ECC Generation 425
Summary of ECC Operations 426
R4400 Master/Checker Mode 430
Connecting a System in Lock Step 431
Master-Listener Configuration 432
Cross-Coupled Checking Configuration 433
Fault Detection 435
Reset Operation 436
Fault History 436

A

CPU Instruction Set Details

B

FPU Instruction Set Details

C

Subblock Ordering

Sequential Ordering C-2
Subblock Ordering C-2

D

Output Buffer Δi/Δt Control Mechanism

Mode Bits D-1
Delay Times D-2

E

PLL Passive Components

F

Coprocessor 0 Hazards

G

R4000 Pinouts

Pinout of R4000PC G-2
Pinout of R4000MC/SC Package Pinout G-5

Index