

The AJIT processor

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Contents

1	AJIT Processor Family	9
1.1	AJIT processor family	9
1.2	Memory subsystems in AJIT processor cores	10
1.3	Debug support mechanisms in AJIT processor cores	10
1.4	Micro-architectural details about the AJIT CPU threads	11
1.5	AJIT CPU: exceptions and interrupts	11
1.6	AJIT processor interfaces	12
1.7	AJIT Processor core: development tools	12
1.8	AJIT Processor core: ASIC history	12
1.9	Looking ahead	13
2	The AJIT Multi-threaded Core	15
2.1	The AJIT single-thread core	15
2.2	The AJIT dual-thread core	15
2.3	The AJIT lite core	15
3	The AJIT central processing unit (CPU)	19
3.1	Instruction Set Architecture	19
3.1.1	Instruction-wise implementation decisions	19
3.1.2	Exceptions	20
3.2	ASR mappings	22
3.2.1	Listing of instructions	22
4	64-bit ISA extensions: overview	31
4.1	Integer-unit extensions: Arithmetic-logic instructions	31
4.2	Integer-unit extensions: SIMD (Vector) instructions	34
4.3	Integer-unit extensions: SIMD REDUCE instructions	35
4.4	Vector floating point instructions	39
4.5	Floating point REDUCE	40
4.6	Half precision conversion instructions	41
4.7	CSWAP insruction	41
4.7.1	AJIT CPU (Thread) internal structure	42
4.7.2	Instruction timings in the AJIT CPU	43
4.8	AJIT thread Identification Codes	44

5	The AJIT memory unit	45
5.1	The AJIT Data Cache	45
5.2	The AJIT Instruction Cache	46
5.3	The AJIT Memory Management Unit (MMU)	46
5.4	The AJIT Level-2 Cache	47
6	AJIT processor interfaces	49
6.1	AJIT core bus interface	49
6.2	AJIT FIFO bus interface	50
6.3	ACB/AFB Protocol and Timing	50
6.3.1	Timing of a single transfer	52
6.4	Bridges	52
7	Basic peripherals available for AJIT systems	55
7.1	The AJIT multi-core interrupt controller	55
7.1.1	Registers and their memory mapping	55
7.1.2	TIC state machines	56
7.1.3	VHDL	56
7.2	The default count-down timer	57
7.2.1	VHDL	57
7.3	The simple serial device	57
7.3.1	Using the serial device: RX	59
7.3.2	Using the serial device: TX	59
7.3.3	Restrictions on accesses to the serial registers	59
7.3.4	VHDL	59
7.4	AFB I2C master controller	60
7.4.1	VHDL	61
7.5	Self Tuning UART	61
7.5.1	VHDL	62
7.6	AFB SPI Master	62
7.6.1	VHDL details	64
7.7	AFB SPI Flash controller	64
7.7.1	VHDL	65
7.8	Processor core add-ons	65
7.8.1	GlueModules	65
7.8.2	GenericCoreAddOnLib	66
8	AJIT Development Tools	69
8.1	The AJIT Debug Monitor	69
8.1.1	Synopsys	69
8.1.2	Reset/mode control/observe	70
8.1.3	Initial PC/NPC/PSR control/observe	71
8.1.4	State register control/observe	72
8.1.5	Integer general purpose register control/observe commands	72
8.1.6	Floating point general purpose register control/observe commands	73

8.1.7	Memory control/observe commands	73
8.1.8	Load memory map file	73
8.1.9	Execute script file	74
8.1.10	Start/stop GDB server	74
8.1.11	Help, quit, log	74
8.1.12	Use Scenario	75
8.2	Processor models: C reference ISA model	76
8.3	Compilation tools	78
8.3.1	compileToSparcUclibc.py	78
8.3.2	makeLinkerScript.py	80
8.3.3	genVmapAsm	81
8.3.4	The init.s file	82
9	Preparing a FLASH image for booting an application	83
9.1	Compiling the application	83
9.2	Prepare the boot image	84
10	The AJIT FPGA based prototyping platforms	87
10.1	KC705 board-based FPGA prototype of AJIT Single-board-computer	87
10.1.1	Using the KC705 platform	88
10.1.2	Writing programs for the KC705 platform	89
10.2	VC709 board-based FPGA prototype of AJIT Single-board-computer	89
10.2.1	Writing programs for the VC709 platform	90
10.2.2	Setup for using the VC709 platform	91
11	The debug infrastructure for AJIT processors	93
11.1	On chip debug scheme	93

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Chapter 1

AJIT Processor Family

The AJIT processor family consists of a variety of configurations and is intended for the high performance embedded system and IOT applications.

1.1 AJIT processor family

The processors are built around the following building blocks.

- A central processing unit (AJIT32 CPU), also known as a **thread**, which implements the SPARC-V8 (IEEE 1754-1994) instruction set architecture. An extended version of the CPU (AJIT64 CPU) is also implemented. The AJIT64 CPU supports the SPARC-V8 ISA, and also supports vector instructions for DSP/AIML/Embedded applications.
- A memory unit (MUNIT) which includes data and instruction caches, as well as a memory management unit.
- A coherent memory controller with snoop based cache coherence.
- A programmable interrupt controller with a per thread interrupt state machine.
- Each AJIT processor can be configured with up to four AJIT cores.
- Each AJIT core can be configured with either one or two hardware threads (CPU's).
- Each AJIT CPU can have two flavours:
 - The base CPU is an implementation of the IEEE std. 1754-1994 (SPARC V8) instruction set. We call this the AJIT32 CPU.
 - An extended version of this CPU implements the SPARC V8 instruction set with extensions that support 64-bit integer operations as well as vector operations on 8/16/32-bit integer data. We call a CPU with this extensions as the AJIT64 CPU.

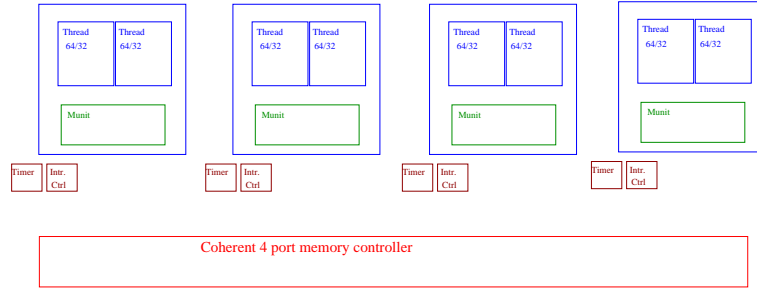


Figure 1.1: AJIT processor with 4 cores, each with 2 threads

Thus, an AJIT processor can have a minimum configuration of one core, one cpu thread per core, with each CPU thread being an AJIT32 CPU (implementing the base SPARC-V8 ISA). The maximum configuration of an AJIT processor consists of four cores, each of which has two CPU threads, with each CPU thread being an AJIT64 CPU (implementing the SPARC-V8 ISA plus vector extensions), and is shown in Figure 1.1. This provides a wide array of choices to an embedded system designer.

1.2 Memory subsystems in AJIT processor cores

Each AJIT core has a full featured memory subsystem. This memory subsystem is shared by the CPU threads within an AJIT core.

- The AJIT processor core includes a 32 Kbyte direct-mapped or 4-way set associative instruction cache (ICACHE), and a 32 Kbyte direct-mapped or 4-way set associative, write-through-allocate data cache (DCACHE). The cache access latency on a hit is 2 cycles. The processor core also includes a memory-management-unit (MMU), an implementation of the Sparc-reference MMU (SRMMU) with an 278-entry translation-lookaside-buffer (TLB) and hardware implementation of a 4-level page table walk.
- The memory subsystem includes a snoop based cache coherence mechanism for building shared memory multi-core systems.

1.3 Debug support mechanisms in AJIT processor cores

Each AJIT processor core has sophisticated debug support mechanisms for comprehensive debugging of system code.

- For debug support, each AJIT CPU thread includes a dedicated hardware debug unit which offers complete observability and controllability of internal processor state. The hardware debug unit can be used in conjunction

with the GDB debugger to offer real-time debug capability for the AJIT CPU thread.

- Each AJIT CPU thread can also generate an execution trace which can be captured (at run time) and stored into a trace buffer which uses the system memory.

1.4 Micro-architectural details about the AJIT CPU threads

- Each AJIT CPU thread has a single issue, in-order pipeline. Thus, the CPU thread is not vulnerable to micro-architectural side-channel attacks. The pipeline runs at a rate of 1 instruction per cycle, and is a 7 stage pipeline with full floating point (IEEE 754) support. The pipeline includes an integer divider, as well as floating point square-root and divider (single and double precision) units.
- Includes branch prediction and speculative execution of streams: uses a 256-entry single bit branch predictor.
- Fully pipelined load/store unit with total load/store ordering.
- Fully pipelined floating point unit (single precision and double precision). Denormalized numbers as specified in IEEE 754 are fully supported.
- All FP operations except divide and square root are pipelined, and normally take two clock cycles. If the result of an operation needs to be delivered as a denormal (a rare event), then an additional two cycles are consumed.

1.5 AJIT CPU: exceptions and interrupts

An AJIT CPU has a well defined set of exceptions (as defined in the SPARC-V8 standard), which includes hardware as well as software generated exceptions. Further, each AJIT CPU can respond to 15 possible interrupt sources. Trap handling is done transparently by the CPU using a vectored trap mechanism. Interrupts are sampled at every instruction, in the decode stage of the pipeline.

All exceptions are handled **precisely** (including floating point exceptions). This simplifies the job of writing exception handlers since the state of the processor at the point of appearance of the exception is preserved exactly. The minimum trap and interrupt latency of the AJIT processor core is 12 clock cycles.

1.6 AJIT processor interfaces

The AJIT processor native system interface is called the AJIT-CORE-BUS and consists of a request-response pair of FIFO interfaces. Bridges to AXI and AHB interfaces are available to interface to a wide variety of memory and peripheral devices.

1.7 AJIT Processor core: development tools

A complete software development chain is available. The existing GCC compiler, GDB debugger and the Linux kernel for the SPARC-V8 ISA are compatible with the AJIT processor core. Binary utils support for both AJIT32 and AJIT64 CPU's is available.

In addition,

- A full featured processor emulator (written in C) is available for use by software developers and system designers.
- FPGA prototypes of the processor configurations listed earlier are also available.
- A suite of tools for software development (trap handlers, timer control, interrupt handling, printing etc.) and compilation scripts are available for systematic management of the entire software development process.

1.8 AJIT Processor core: ASIC history

A proof-of-concept implementation in 180nm technology was carried out at SCL Chandigarh.

- 7mm X 7mm, 144 functional I/O's, 256 pin package.
- 0.5 W at 66 MHz (slow corner).

An implementation of the AJIT processor core for a NAVIC GPS+IRNSS receiver has been completed and is being fabricated in 65nm technology at UMC (Taiwan).

- 4mm X 4mm die size (56 I/O, 100 total pads).
- CPU can run at 400MHz, system is operated at 125 MHz.
- System power: 250mW @ 125MHz.

1.9 Looking ahead

In the rest of this document, we will describe:

- Multi-core features.
- Single-core features.
- The AJIT CPU in two flavours: base SPARC-V8 and base SPARC-V8 with vector extensions.
 - ISA, exceptions and trap numbering.
- The AJIT core memory unit.
 - Data and Instruction caches, Memory-management-unit.
- Peripherals currently available for the AJIT core.
- Tools: for building applications.
- Available FPGA prototypes.
- Debug infrastructure using on-CPU hardware debug unit, as well as GDB remote debug process.

Chapter 2

The AJIT Multi-threaded Core

The AJIT Multi-threaded core is constructed using one or two AJIT CPU's, which work together with a shared memory unit.

2.1 The AJIT single-thread core

The single-thread core is illustrated in Figure 2.1. As indicated, the core integrates an AJIT CPU (either AJIT32 CPU or AJIT64 CPU) with the memory unit. The AJIT CPU has its own debug interface and its own interrupt input. This is the minimal AJIT core configuration.

2.2 The AJIT dual-thread core

The dual-thread core is illustrated in Figure 2.2. As indicated, the core integrates two identical AJIT CPU's (either AJIT32 CPU or AJIT64 CPU) with a shared memory unit. Each AJIT CPU has its own debug interface and its own interrupt input and work indendependently.

2.3 The AJIT lite core

The single-thread AJIT lite core omits the floating point unit and the memory management unit from the single threaded core in Figure 2.1. This results in a 50% saving of resources over the minimal single threaded core.

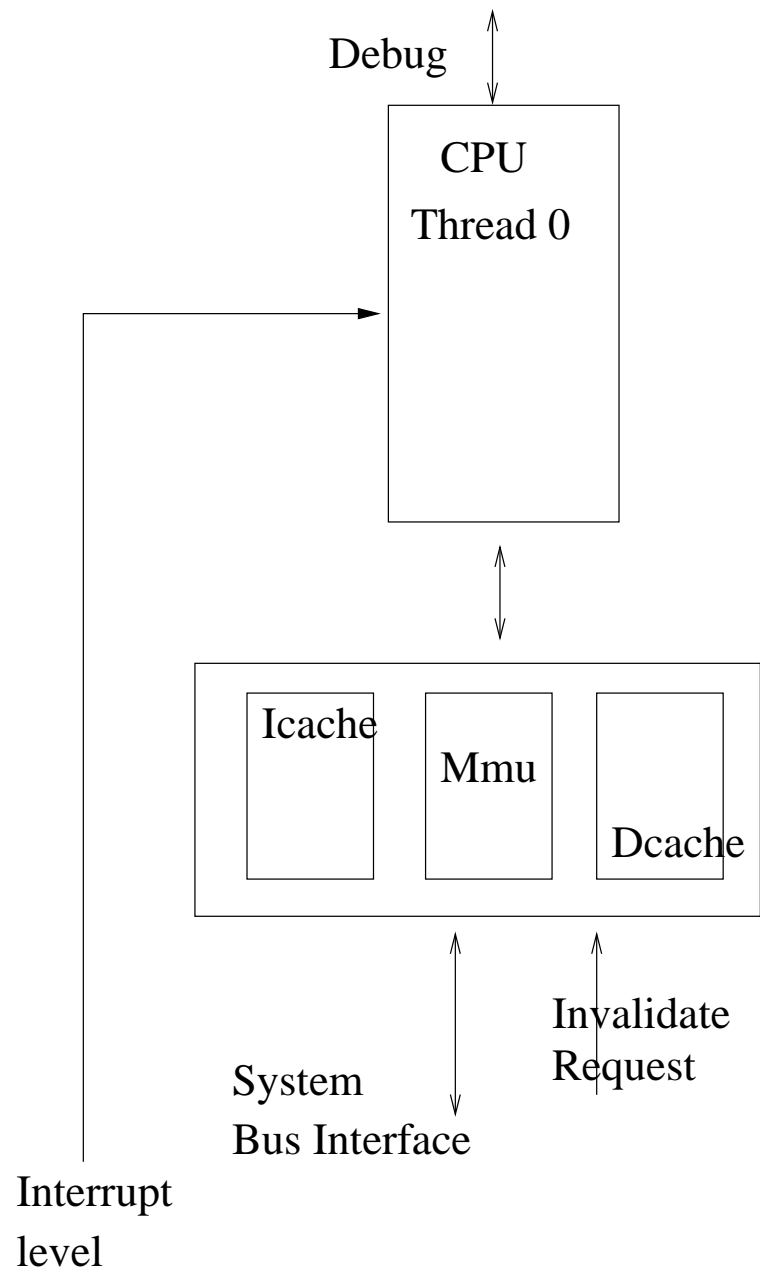


Figure 2.1: AJIT single-threaded core

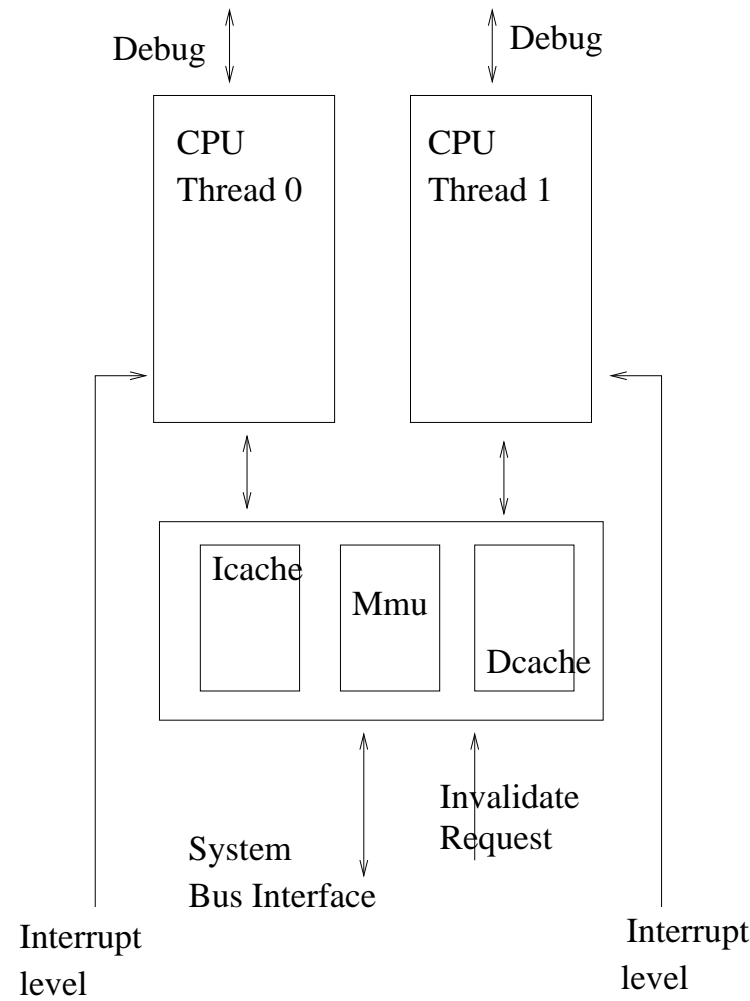


Figure 2.2: AJIT dual-threaded core

Chapter 3

The AJIT central processing unit (CPU)

We describe the central processing unit (CPU) of the AJIT processor core. Often, we will refer to the CPU as a *thread*.

3.1 Instruction Set Architecture

An AJIT thread implements the SPARC-V8 instruction set architecture (draft IEEE standard 1754-1994) [1]. Specific decisions made in the implementation are listed below. All design decisions are consistent with the SPARC V8 ISA specification.

3.1.1 Instruction-wise implementation decisions

The instructions in the SPARC V8 ISA fall into the following classes: data-transfer instructions (listed in Figure 3.3), miscellaneous instructions (listed in Figure 3.4), integer ALU instructions (listed in Figure 3.5), integer TICC instructions (listed in Figure 3.6), control transfer instructions (listed in Figure 3.7), and floating point instructions (listed in Figure 3.8).

- **Data-transfer instructions:** All data transfer instructions are implemented, except for the following (which are optional in the SPARC-V8 ISA).

STDFQ	Not implemented (no FP queue)
STC	Not implemented (no Co-processor)
STDC	Not implemented (no Co-processor)
STCSR	Not implemented (no Co-processor)
STDCQ	Not implemented (no Co-processor)

- **Miscellaneous instructions:** All miscellaneous instructions are implemented.
- **Integer ALU instructions:** All integer ALU instructions are implemented.
- **Floating-point instructions:** All required floating point instructions are implemented. The following Quad-precision floating point instructions are not implemented.

FqTOi	Not implemented
FsTOq	Not implemented
FdTOq	Not implemented
FqTOs	Not implemented
FqTOd	Not implemented
FSQRTq	Not implemented
FADDq	Not implemented
FSUBq	Not implemented
FMULq	Not implemented
FdMULq	Not implemented
FDIVq	Not implemented
FCMPq	Not implemented
FCMPEq	Not implemented

- **Control transfer instructions:** All required control transfer instructions are implemented. Since there is no coprocessor included in the CPU, coprocessor branches are not implemented.
- **Trap instructions:** All trap instructions are implemented.

3.1.2 Exceptions

In Figure 3.1, we list the exceptions are generated and handled by the AJIT processor core. All exceptions are handled in a **precise** manner. If there is an exception, the processor generates a 32-bit trap-vector (TV). We list the indices of the trap-vector which correspond to the distinct exceptions.

On a trap, the CPU jumps to a vectored trap location. This location is determined as

$$(TBR \ \& \ (\sim TT_MASK)) \mid (TRAP_ID \ll 4)$$

where TBR is the trap base register, $TT_MASK = 0xfffff00f$, and $TRAP_ID$ is the trap identifier. For the traps listed above, the identifiers are shown in Figure 3.2.

Mnemonic	TV-index	explanation
RT	0	reset-trap
IAE	4	instruction-access-exception
AT	3	annul-trap
PI	8	privileged instruction.
II	9	illegal instruction
FPD	11	fp-disabled
CPD	12	co-processor disabled
WOF	14	window-overflow
WUF	15	window-underflow
UA	16	unaligned-address
FPE	17	fp-exception
		invalid-reg
		sequence-error
		fp-unimpl-instr
		fp-ieee-754-trap
DAE	20	data-access-exception.
TOF	21	tag-overflow
IDZ	22	iu-div-by-zero
TT	23	trap-instruction-trap

Figure 3.1: Exceptions generated by the AJIT processor core

Mnemonic	TRAP_ID
IAE	0x1
II	0x2
PI	0x3
FPD	0x4
WOF	0x5
WUF	0x6
UA	0x7
FPE	0x8
DAE	0x9
TOF	0xA
CPD	0x24
IDZ	0x2A
TT	0x80 ticc_trap_type
interrupt (when interrupt-level != 0)	
INTR	0x10 interrupt-level

Figure 3.2: Trap Identifiers

3.2 ASR mappings

The following ancillary state registers (ASR's) are used by the AJIT CPU implementation.

- **Free running counter:** ASR[31] and ASR[30] implement a free running 64-bit counter which runs at the processor clock. Writes to these registers are ignored.
- **CPU Identity:** ASR[29] stores a 32-bit value (read-only) which has the following format

```

[31:16]  RESERVED
[15:8]   Core Id to which CPU
          belongs
[7:0]    CPU Id within the core.
```

All other ASR's are implemented as R/W registers without any assigned mappings.

3.2.1 Listing of instructions

We list the instructions in the SPARC-V8 ISA and their status within the AJIT CPU implementation. For each instruction, we also indicate the exceptions that

it can raise.

In Figure 3.3, we show the data-transfer instructions.

In Figure 3.4, we show the miscellaneous instructions.

In Figure 3.5, we show the integer unit instructions.

In Figure 3.6, we show the trap (TICC) instructions.

In Figure 3.7, we show the control transfer instructions. Note that co-processor branch instructions are not currently implemented.

In Figure 3.8, we show the floating point instructions.

The co-processor operations are not implemented (Figure 3.9).

Instruction	Exceptions	Notes
LDSB	DAE	
LDSH	DAE, UA	
LDUB	DAE	
LDUH	DAE, UA	
LD	DAE, UA	
LDD	DAE, UA	
LDF	DAE, UA	
LDDF	DAE, UA	
LDFSR	FPD	
LDC	CPD	
LDDC	CPD	
LDCSR	CPD	
LDSBA	DAE, PI, II	
LDSHA	DAE, PI, II, UA	
LDUBA	DAE, PI, II	
LDUHA	DAE, PI, II, UA	
LDA	DAE, PI, II, UA	
LDDA	DAE, PI, II, UA	
STB	DAE	
STH	DAE, UA	
ST	DAE	
STD	DAE, UA	
STF	DAE, UA	
STDF	DAE, UA	
STFSR	FPD	
STDFQ	FPD	Not implemented (no FP queue)
STC	CPD	Not implemented (no CP)
STDC	CPD	Not implemented (no CP)
STCSR	CPD	Not implemented (no CP)
STDCQ	CPD	Not implemented (no CP)
STBA	DAE, PI, II	
STHA	DAE, PI, II, UA	
STA	DAE, PI, II, UA	
STDA	DAE, PI, II, UA	
LDSTUB	DAE	
LDSTUBA	DAE, PI, II	
SWAP	DAE	
SWAPA	DAE, PI, II	

Figure 3.3: Actually implemented data transfer instructions and generated exceptions

SETHI		
NOP		
SAVE	WOF	
RESTORE	WUF	
RDY	PI	
RDASR	PI	
RDPSR	PI	
RDWIM	PI	
RDTBR	PI	
WRY	PI	
WRASR	PI	
WRPSR	PI, II	
WRWIM	PI	
WRTBR	PI	
STBAR		NOP.
UNIMP	II	Always generates Illegal instruction trap.
FLUSH		Flushes entire ICACHE and DCACHE.

Figure 3.4: Actually implemented miscellaneous instructions and exceptions

AND	
ANDcc	
ANDN	
ANDNcc	
OR	
ORcc	
ORN	
ORNcc	
XOR	
XORcc	
XNOR	
XNORcc	
SLL	
SRL	
SRA	
ADD	
ADDcc	
ADDX	
ADDXcc	
TADDcc	
TADDccTV	TOF
SUB	
SUBcc	
SUBX	
SUBXcc	
TSUBcc	
TSUBccTV	TOF
MULScc	
UMUL	
SMUL	
UMULcc	
SMULcc	
UDIV	IDZ
SDIV	IDZ
UDIVcc	IDZ
SDIVcc	IDZ

Figure 3.5: Integer ALU instructions and associated traps

TA	TT
TN	TT
TNE	TT
TE	TT
TG	TT
TLE	TT
TGE	TT
TL	TT
TGU	TT
TLEU	TT
TCC	TT
TCS	TT
TPOS	TT
TNEG	TT
TVC	TT
TVS	TT

Figure 3.6: TICC instructions and associated traps

BA
 BN
 BNE
 BE
 BG
 BLE
 BGE
 BL
 BGU
 BLEU
 BCC
 BCS
 BPOS
 BNEG
 BVC
 BVS

CALL
 JMPL UA
 RETT II, PI, UA

Floating point branch.

FBA FPD
 FBN FPD
 FBU FPD
 FBG FPD
 FBUG FPD
 FBL FPD
 FBUL FPD
 FBLG FPD
 FBNE FPD
 FBE FPD
 FBUE FPD
 FBGE FPD
 FBUGE FPD
 FBLE FPD
 FBULE FPD
 FBO FPD

Co-processor branch

CBA	CPD	Not implemented
CBN	CPD	Not implemented
CB3	CPD	Not implemented
CB2	CPD	Not implemented
CB23	CPD	Not implemented
CB1	CPD	Not implemented
CB13	CPD	Not implemented
CB12	CPD	Not implemented
CB123	CPD	Not implemented
CB0	CPD	Not implemented
CB03	CPD	Not implemented
CB02	CPD	Not implemented
CB023	CPD	Not implemented
CB01	CPD	Not implemented
CB013	CPD	Not implemented
CB012	CPD	Not implemented

FiT0s	FPD	
FiT0d	FPD	
FiT0q	FPD	
FsT0i	FPD, FPE	
FdT0i	FPD, FPE	
FqT0i	FPD, FPE	Not implemented
FsT0d	FPD, FPE	
FsT0q	FPD, FPE	Not implemented
FdT0s	FPD, FPE	
FdT0q	FPD, FPE	Not implemented
FqT0s	FPD, FPE	Not implemented
FqT0d	FPD, FPE	Not implemented
FMOVs	FPD	
FNEGs	FPD	
FABSS	FPD	
FSQRTs	FPD, FPE	
FSQRTd	FPD, FPE	
FSQRTq	FPD, FPE	Not implemented
FADDs	FPD, FPE	
FADDd	FPD, FPE	
FADDq	FPD, FPE	Not implemented
FSUBs	FPD, FPE	
FSUBd	FPD, FPE	
FSUBq	FPD, FPE	Not implemented
FMULs	FPD, FPE	
FMULd	FPD, FPE	
FMULq	FPD, FPE	Not implemented
FsMULd	FPD, FPE	
FdMULq	FPD, FPE	Not implemented
FDIVs	FPD, FPE	
FDIVd	FPD, FPE	
FDIVq	FPD, FPE	Not implemented
FCMPs	FPD	
FCMPd	FPD	
FCMPq	FPD, FPE	Not implemented
FCMPEs	FPD, FPE	
FCMPed	FPD, FPE	
FCMPEq	FPD, FPE	Not implemented

Figure 3.8: Floating point instructions and associated traps

CPop1	CPD	Not implemented
CPop2	CPD	Not implemented

Figure 3.9: Coprocessor instructions and associated traps

Chapter 4

64-bit ISA extensions: overview

The AJIT processor implements the Sparc-V8 ISA. We have extended this ISA to provide support for a native 64-bit integer datatype. The extensions use the existing instruction encodings to the maximum extent possible.

All proposed extensions are RegisterXRegister -> Register,Condition-codes type instructions. The load/store instructions are not modified.

We list the additional instructions in the subsequent sections. In each case, only the differences in the encoding relative to an existing Sparc-V8 instruction are provided.

4.1 Integer-unit extensions: Arithmetic-logic instructions

These instructions provide 64-bit arithmetic/logic support in the integer unit. The instructions work on 64-bit register pairs in most cases. Register-pairs are identified by a 5-bit even number (lowest bit must be 0).

The instructions function the same as ADD/SUB/UMUL/UDIV/SMUL/SDIV and their CC versions. The trapping behaviour of the *TV instructions is not extended to 64-bit values.

The *MULSCC operation is not extended to 64 bits, because we expect to have a divider in all implementations.

ADDD

encoding: same as ADD, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) + rs2(pair)

ADDDCC

encoding: same as ADDCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) + rs2(pair), set C,0,Z,N

SUBD

encoding: same as SUB, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) - rs2(pair)

SUBDCC

encoding: same as SUBCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) - rs2(pair), set C,0,Z,N

SLLD

encoding: same as SLL, but with Instr[7:6]=2.
 if imm bit (Instr[13]) is 1, then Instr[5:0] is the shift-amount.
 else shift-amount is the lowest 6 bits of rs2. Note that rs2
 is a 32-bit register.
 rd(pair) <- rs1(pair) << shift-amount

SRLD

encoding: same as SRL, but with Instr[7:6]=2.
 if imm bit (Instr[13]) is 1, then Instr[5:0] is the shift-amount.
 else shift-amount is the lowest 6 bits of rs2. Note that rs2
 is a 32-bit register.
 rd(pair) <- rs1(pair) >> shift-amount

SRAD

encoding: same as SRA, but with Instr[7:6]=2.
 if imm bit (Instr[13]) is 1, then Instr[5:0] is the shift-amount.
 else shift-amount is the lowest 6 bits of rs2. Note that rs2
 is a 32-bit register.
 rd(pair) <- rs1(pair) >> shift-amount (with sign extension).

UMULD

encoding: same as UMUL, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) * rs2(pair)

UMULDCC

encoding: same as UMULCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) * rs2(pair), sets Z, Overflow

SMULD

encoding: same as SMULD, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) * rs2(pair) (signed)

SMULDCC

encoding: same as SMULCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) * rs2(pair) (signed)
 sets condition codes Z,N,Overflow

UDIVD

4.1. INTEGER-UNIT EXTENSIONS: ARITHMETIC-LOGIC INSTRUCTIONS33

encoding: same as UDIV, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) / rs2(pair)
note: can generate div-by-zero trap.

UDIVDCC
encoding: same as UDIVCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) / rs2(pair)
sets condition codes Z,Overflow
note: can generate div-by-zero trap.

SDIVD
encoding: same as SDIV, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) / rs2(pair) (signed)

SDIVDCC
encoding: same as SDIVCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) / rs2(pair) (signed)
sets condition codes Z,N,Overflow
note: can generate div-by-zero trap.

ORD
encoding: same as OR, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) | rs2(pair)

ORDCC
encoding: same as ORCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) | rs2(pair), sets Z.

ORDN
encoding: same as ORN, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) | (~rs2(pair))

ORDNCC
encoding: same as ORNCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) | (~rs2(pair)), sets Z
sets Z.

XORD
encoding: same as XOR, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) ^ rs2(pair)

XORDCC
encoding: same as XORCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) ^ rs2(pair), sets Z
sets Z.

XNORD
encoding: same as XNOR, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) ^ rs2(pair)

XNORDCC
encoding: same as XNORCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
rd(pair) <- rs1(pair) ^ rs2(pair), sets Z

ANDD

encoding: same as AND, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) . rs2(pair)

ANDDCC

encoding: same as ANDCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) . rs2(pair), sets Z

ANDDN

encoding: same as ANDN, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd(pair) <- rs1(pair) . (~rs2(pair))

ANDDNCC

encoding: same as ANDNCC, but with Instr[13]=0 (i=0), and Instr[5]=1.
 rd <- rs1 . (~rs2), sets Z

4.2 Integer-unit extensions: SIMD (Vector) instructions

These instructions are vector instructions which work on two source registers (each a 64 bit register pair), and produce a 64-bit vector result. The vector elements can be 8-bit/16-bit/32-bit.

VADDD8, VADDD16, VADDD32

encoding: same as ADDD, but with Instr[13]=0 (i=0), and Instr[6:5]=2.
 bits Instr[9:7] are a 3-bit field, which specify the data type

001	byte	(VADDD8)
010	half-word (16-bits)	(VADDD16)
100	word (32-bits)	(VADDD32)

performs a vector operation by considering the 64-bit operands as a vector of objects with specified data-type.

```
vadd8 rs1,rs2, rd
vadd16
vadd32
```

VSUBD8, VSUBD16, VSUBD32

encoding: same as SUBD, but with Instr[13]=0 (i=0), and Instr[6:5]=2.
 bits Instr[9:7] are a 3-bit field, which specify the data type

001	byte	(VSUBD8)
010	half-word (16-bits)	(VSUBD16)
100	word (32-bits)	(VSUBD32)

performs a vector operation by considering the 64-bit operands as a vector of objects with specified data-type.

```
vsubd8
vsubd16
vsubd32
```

VUMULD8, VUMULD16, VUMULD32

encoding: same as UMULD, but with Instr[13]=0 (i=0), and Instr[6:5]=2.
bits Instr[9:7] are a 3-bit field, which specify the data

type

```
001 byte      (VMULD8)
010 half-word (16-bits) (VMULD16)
100 word (32-bits)      (VMULD32)
```

performs a vector operation by considering the 64-bit operands as
a vector of objects with specified data-type.

```
vumuld8
vumuld16
vumuld32
```

VSMULD8, VSMULD16, VSMULD32

encoding: same as SMULD, but with Instr[13]=0 (i=0), and Instr[6:5]=2.
bits Instr[9:7] are a 3-bit field, which specify the data

type

```
001 byte      (VSMULD8)
010 half-word (16-bits) (VSMULD16)
100 word (32-bits)      (VSMULD32)
```

performs a vector operation by considering the 64-bit operands as
a vector of objects with specified data-type.

```
vsmuld8
vsmuld16
vsmuld32
```

4.3 Integer-unit extensions: SIMD REDUCE instructions

These instructions are vector instructions which reduce a 64 bit source register to a destination using an associative operation.

ADDDREDUCE8

op=2, op3[3:0]=0xd, op3[5:4]=0x2, contents[7:0] of rs2 specify a mask.

encoding

```
Instr[31:30] (op) = 0x2
Instr[29:25] (rd) 32-bit register.
Instr[24:19] (op3) = 101101
Instr[18:14] (rs1) lowest bit assumed 0.
```

```

Instr[13]    (i) = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]
    = 1 for byte reduce
    contents[7:0] of rs2 specify a mask.
Instr[6:5]   (zero)
Instr[4:0]   (rs2) 32-bit register is read.

rd <- (m7 ? rs1_7 : 0x0) + (m6 ? rs1_6 : 0x0) + (m5 ? rs1_5:0) ...
      + (m0 ? rs1_0 : 0x0)

```

```

addreduce8 %rs1, %rs2, %rd
    (all additions are twos-complement, 8-bit additions)

```

ADDDREDUCE16

```

op=2, op3[3:0]=0xd, op3[5:4]=0x2, contents[3:0] of rs2 specify a mask.
encoding
Instr[31:30] (op) = 0x2
Instr[29:25] (rd) 32-bit register.
Instr[24:19] (op3) = 101101
Instr[18:14] (rs1) lowest bit assumed 0.
Instr[13]    (i) = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]   = 2 for half word reduce
    contents[3:0] of rs2 specify a mask.
Instr[6:5]   (zero)
Instr[4:0]   (rs2) 32-bit register is read.

rd <- (m3 ? rs1_hw_3 : 0x0) + (m2 ? rs1_hw_2 : 0x0)
      + (m1 ? rs1_hw_1 : 0x0) + (m0 ? rs1_hw_0 : 0x0)

```

```

addreduce16 %rs1, %rs2, %rd
    (all additions are twos-complement, 16-bit additions)

```

ORDREDUCE8

```

op=2, op3[3:0]=0xe, op3[5:4]=0x2, contents[7:0] of rs2 specify a mask.
encoding
Instr[31:30] (op) = 0x2
Instr[29:25] (rd) rd is a 32-bit register.
Instr[24:19] (op3) = 101110
Instr[18:14] (rs1) lowest bit assumed 0.
Instr[13]    (i) = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]

```

4.3. INTEGER-UNIT EXTENSIONS: SIMD REDUCE INSTRUCTIONS 37

```

    = 1 for byte reduce
    contents[7:0] of rs2 specify a mask.
Instr[6:5] (zero)
Instr[4:0] (rs2) 32-bit register is read.

rd <- (m7 ? rs1_7 : 0x0) | (m6 ? rs1_6 : 0x0) | (m5 ? rs1_5:0) ...
      | (m0 ? rs1_0 : 0x0)

ordreduce8 %rs1, %rs2, %rd

```

```

ORDREDUCE16
op=2, op3[3:0]=0xe, op3[5:4]=0x2, contents[3:0] of rs2 specify a mask.
encoding
Instr[31:30] (op) = 0x2
Instr[29:25] (rd) rd is a 32-bit register.
Instr[24:19] (op3) = 101110
Instr[18:14] (rs1) lowest bit assumed 0.
Instr[13] (i) = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]
    = 2 for half-word reduce
    contents[3:0] of rs2 specify a mask.
Instr[6:5] (zero)
Instr[4:0] (rs2) 32-bit register is read.

rd <- (m3 ? rs1_hw_3 : 0x0) | (m2 ? rs1_hw_2 : 0x0)
      | (m1 ? rs1_hw_1: 0x0) | (m0 ? rs1_hw_0 : 0x0)

ordreduce16 %rs1, %rs2, %rd

```

```

ANDDREDUCE8
op=2, op3[3:0]=0xf, op3[5:4]=0x2, contents[7:0] of rs2 specify a mask.
encoding
Instr[31:30] (op) = 0x2
Instr[29:25] (rd) rd is a 32-bit register.
Instr[24:19] (op3) = 101111
Instr[18:14] (rs1) lowest bit assumed 0.
Instr[13] (i) = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]
    = 1 for byte reduce
    contents[7:0] of rs2 specify a mask.
Instr[6:5] (zero)
Instr[4:0] (rs2) 32-bit register is read.
rd <- ( (m7 ? rs1_7 : 0xff) . (m6 ? rs1_6 : 0xff) .... (m0 ? rs1_0 : 0xff))

```

```
anddreduce8 %rs1, %rs2, %rd
```

ANDDREDUCE16

op=2, op3[3:0]=0xf, op3[5:4]=0x2, contents[3:0] of rs2 specify a mask.
encoding

```
Instr[31:30] (op) = 0x2
Instr[29:25] (rd)   rd is a 32-bit register.
Instr[24:19] (op3) = 101111
Instr[18:14] (rs1)  lowest bit assumed 0.
Instr[13]    (i)    = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]
    = 2 for half-word reduce
    contents[3:0] of rs2 specify a mask.
Instr[6:5]   (zero)
Instr[4:0]   (rs2)  32-bit register is read.
```

```
rd <- (m3 ? rs1_hw_3 : 0x0) + (m2 ? rs1_hw_2 : 0x0)
      + (m1 ? rs1_hw_1 : 0x0) + (m0 ? rs1_hw_0 : 0x0)
```

```
anddreduce16 %rs1, %rs2, %rd
```

XORDREDUCE8

op=2, op3[3:0]=0xe, op3[5:4]=0x3, contents[7:0] of rs2 specify a mask.
encoding

```
Instr[31:30] (op) = 0x2
Instr[29:25] (rd)   rd is a 32-bit register.
Instr[24:19] (op3) = 111110
Instr[18:14] (rs1)  lowest bit assumed 0.
Instr[13]    (i)    = 0 (ignored)
Instr[12:10] (zero)
Instr[9:7]
    = 1 for byte reduce
    contents[7:0] of rs2 specify a mask.
```

```
Instr[4:0]   (rs2)  32-bit register is read.
Instr[6:5]   (zero)
```

```
rd <- (m7 ? rs1_7 : 0) ^ (m6 ? rs1_6 : 0) ^ (m5 ? rs1_5 : 0) ...
      ^ (m0 ? rs1_0 : 0)
```

```
xordreduce8 %rs1, %rs2, %rd
```

XORDREDUCE16

op=2, op3[3:0]=0xe, op3[5:4]=0x3, contents[3:0] of rs2 specify a mask.
encoding

```
Instr[31:30] (op) = 0x2
Instr[29:25] (rd)   rd is a 32-bit register.
```

```

Instr[24:19] (op3) = 111110
Instr[18:14] (rs1)  lowest bit assumed 0.
Instr[13]      (i)  = 0 (ignored)
Instr[12:10]   (zero)
Instr[9:7]
    = 2 for half-word reduce
    contents[3:0] of rs2 specify a mask.
Instr[4:0]     (rs2)  32-bit register is read.
Instr[6:5]     (zero)

rd <- (m3 ? rs1_hw_3 : 0) ^ (m2 ? rs1_hw_2 : 0)
      ^ (m1 ? rs1_hw_1:0) ^ (m0 ? rs1_hw_0 : 0)

xordreduce16 %rs1, %rs2, %rd

ZBYTEDPOS
op=2, op3[3:0]=0xf, op3[5:4]=0x3, contents[7:0] of rs2/imm-value specify a mask.
encoding
Instr[31:30] (op) = 0x2
Instr[29:25] (rd)  rd is a 32-bit register.
Instr[24:19] (op3) = 111111
Instr[18:14] (rs1)  lowest bit assumed 0.
Instr[13]     (i)  = if 0, use rs2, else Instr[7:0]
Instr[12:5]   = 0 (ignored if i=0)
Instr[4:0]    (rs2, if i=0)
              32-bit register is read.

rd <- [b7_zero b6_zero b5_zero b4_zero .. b0_zero]
      (if mask-bit is zero then b*_zero is zero)

zbytedpos %rs1, %rs2/imm, %rd

```

4.4 Vector floating point instructions

These are vector float operations which work on two single precision operand pairs to produce two single precision results.

```

// SIMD float ops.
// NaN propagated, but no traps.
// For each of these, rs1,rs2,rd are
// considered even numbers pointing to
// a floating point register-pair.
//
VFADD32
op=2, op3=0x34, opf=0x142

```

```

    vfadd32 %f0, %f2, %f4

VFADD16
    // half-precision vector add.
    // opcode to be assigned.
    op=2, op3=0x34, opf=0x143
    vfadd16 %f0, %f2, %f4

VFSUB32
    op=2, op3=0x34, opf=0x144
    vfsub32 %f0, %f2, %f4

VFSUB16
    op=2, op3=0x34, opf=0x145
    // half-precision vector sub.
    // opcode to be assigned.
    vfsub16 %f0, %f2, %f4

VFMUL32
    op=2, op3=0x34, opf=0x146
    vfmul32 %f0, %f2, %f4

VFMUL16
    op=2, op3=0x34, opf=0x147
    // half-precision vector multiply..
    // opcode to be assigned.
    vfmul16 %f0, %f2, %f4

    // these are vector convert instructions
    // to go from i16 to half and vice-versa.
VFI16TOH
    op=2, op3=0x34, opf=0x148
    // convert 4x i16 to 4x half-precision.
    //      rs2-pair is the input, rd-pair is the output
    vfi16toh %f0, %f2

VFHTOI16
    op=2, op3=0x34, opf=0x149
    // convert 4x half-precision to 4x i16.
    //      rs2-pair is the input, rd-pair is the output
    vfhtoi16 %f0, %f2

```

4.5 Floating point REDUCE

These act on a vector and produce a scalar result (as in the integer case).


```

FADDREDUCE16
    op=2, op3=0x34, opf=0x150
    //
    // add the four half-precision numbers in
    // the 64-bit FP register pair rs2, and produce a
    // half-precision result into the destination 32-bit FP register rd.
    //
    // Note: rs1 value is ignored.
    //

```

4.6 Half precision conversion instructions

These instructions allow conversion between IEEE half-precision numbers and IEEE single/double precision numbers and integers.

```

FSTOH
    op=2, op3=0x34, opf=0x151
    // convert single precision value to half-precision value.
    // %f1 -> %f2 (32-bit FP registers)
    //      rs2 is the input, rd is the output
    fstoh %f1, %f2
FHTOS
    op=2, op3=0x34, opf=0x152
    // convert half precision value to single-precision value.
    //      rs2 is the input, rd is the output
    // %f1 -> %f2 (32-bit FP registers)
    fhtos %f1, %f3

```

Note that the double-to-half and half-to-double, int-to-half and half-to-int instructions are not provided. This is because, these transformations are likely to be rarer. Also, the FDTOS, FDTOI, FITOS, FITOD instructions together with the added FSTOH, FHTOS instructions are sufficient (at a minor cost).

4.7 CSWAP insruction

The Sparc-V8 ISA does not include a compare-and-swap (CAS) instruction which is very useful in achieving consensus among distributed agents when the number of agents is ≥ 2 .

We introduce a CSWAP instruction in two flavours

```

CSWAP      rs1, rs2/immediate, rd
    op=3
    op3= 10 1111
    (rest of instruction similar to SWAP)

```

```
cswap %rs1, %rs2/imm, %rd
```

```
CSWAPA    rs1, rs2/immediate, rd-pair, asi
op=3
op3= 11 1111
(rest of instruction similar to SWAPA)
```

```
cswapa %rs1, %rs2/imm, %rd with asi specified.
```

The semantics of the instruction (the entire sequence is atomic) are as follows:

```
TMPVAL = mem[rs1] (load word, lock system bus)
if <rs2/immediate> == TMPVAL
    (store, unlock) mem[rs1] = <rd>
    <rd> = TMPVAL
else
    (store, unlock) mem[rs1] = TMPVAL
```

The store under else is redundant but is required in order to unlock the bus. In the same way as in the SWAP instruction

- `mem[rs1]` is left either with its value prior to the instruction or with the value in `rd`.
- `rd` is left either with its value prior to the instruction or with the value in `mem[rs1]`.

The processor can check `rd` after execution to confirm if the swap succeeded.

4.7.1 AJIT CPU (Thread) internal structure

The internal structure of the AJIT CPU (or thread) is shown in Figure 4.1.

The CPU contains

- A single issue 7-stage (instruction-fetch, decode, operand-fetch, execute, load-store, write-back, retire) execution pipeline, with a 256 entry branch history table and a 1-bit branch predictor.
- An IEEE 754 compliant floating point unit with full support for denormalized numbers, and built-in hardware divide and square-root units.
- A hardware debug support unit which allows full observability and controllability of processor state. It also allows remote real-time debugging via GDB.
- Precise exceptions, low interrupt latency (minimum of 12 cycles).

The caches are virtually indexed, virtually tagged and can be accessed in two clock cycles (on a hit). The Cache line size is 64 bytes, and the miss penalty is 40 cycles. The MMU implements the SPARC SRMMU standard, with a 4-level page table supporting pages of size 4KB, 256KB, 16MB and 4GB.

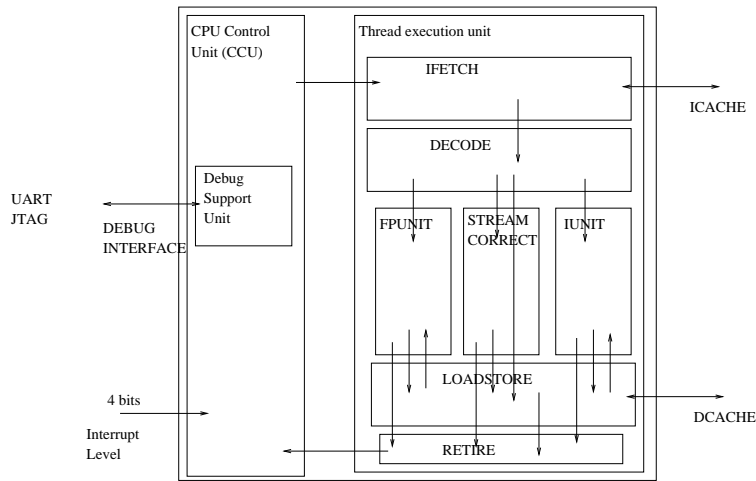


Figure 4.1: 32-bit AJIT CPU (Thread) Internal Structure

4.7.2 Instruction timings in the AJIT CPU

Most instructions in the AJIT CPU take one clock cycle to execute. The time taken by control transfer instructions and load/store instructions is non-deterministic.

- Most integer operations are single cycle, except for divides.

Operation	Cycles	Pipelined?
Logical	1	Yes
Arithmetic	1	Yes
Divide	21	No

- Most floating point operations are pipelined with a latency of two-cycles, except for divides and square-roots.

Operation	Cycles	Pipelined?
fsqrts	16	No
fsqrtd	24	No
fdivs	16	No
fdivd	24	No
Others	2*	Yes

* Add 2 cycles if denormalization of result is needed.

- Load-store operations take two cycles on hits, and 40 cycles on misses (with single cycle SRAM main memory).

Operation	Cycles	Pipelined?
loads	2*	Yes
stores	2*	Yes
swap	8*	Yes
ldstub	8*	Yes

* If there is a hit in Cache.
Miss-penalty to fetch cache line
of 64 bytes is 60 cycles.

- Save/Restore instructions take 3 cycles to execute.

4.8 AJIT thread Identification Codes

Each AJIT thread can be identified by accessing ASR 29. ASR 29 contains the following information:

```
[31:16] 0x5052
[15:8]   Core-id
[7:0]    Thread-id
```

Further, implementation details about the AJIT thread can be identified by accessing ASR 28. ASR 28 contains the following information:

```
[31:30]    L1 Dcache size
00 -> 4KB
01 -> 8KB
10 -> 16KB
11 -> 32KB
[29:28]    L1 Icache size
00 -> 4KB
01 -> 8KB
10 -> 16KB
11 -> 32KB
[27:26]    Log of dcache associativity
[25:24]    Log of icache associativity
[23:20]    Dcache hit latency
[19:16]    Icache hit latency
[15:12]    Log of MMU L3 TLB size
[11:9]     Log of MMU L2 TLB size
[8:7]      Log of MMU L1 TLB size
[6:5]      Log of MMU L0 TLB size
[4:3]      Unused.
[2]        Has NC bypass path.
[1]        2-thread/1-thread.
[0]        set if 64-bit isa else 32-bit isa
```

Chapter 5

The AJIT memory unit

The AJIT memory unit consists of two VIVT caches for data and instruction access, and a shared memory management unit, as shown in Figure 5.1.

5.1 The AJIT Data Cache

The AJIT data cache (DCACHE) is a pipelined implementation which supports precise exceptions. The DCACHE has a cache line size of 64 bytes, and is nominally configured to a size of 32KB, although it can be scaled to sizes down to 4KB.

Two implementations of the DCACHE are available:

- A direct-mapped write-through-allocate virtually-indexed-virtually-tagged (VIVT) cache. The direct mapped version has a hit latency of two clock cycles.
- A 2-way/4-way/8-way set-associative write-through-allocate virtually-indexed-virtually-tagged (VIVT) cache. The set associative version has a hit latency of two or three clock cycles. On average, the associative cache has a hit latency which is 3% higher than that of the direct mapped cache.
- The miss latency of the caches (assuming SRAM main memory) is approximately 36 clock cycles.

Further, the DCACHE has a couple of optimizations.

- The DCACHE provides a fully pipelined bypass access path. Thus, load/store bypass accesses which use ASI values between 0x20 and 0x2f are directly passed through to the system bus, and executed in pipelined fashion. This makes communication between the CPU and peripheral device memory substantially faster.
- The DCACHE provides a fully pipelined access path for accesses to non-cacheable memory locations. The DCACHE maintains a 4-entry TLB

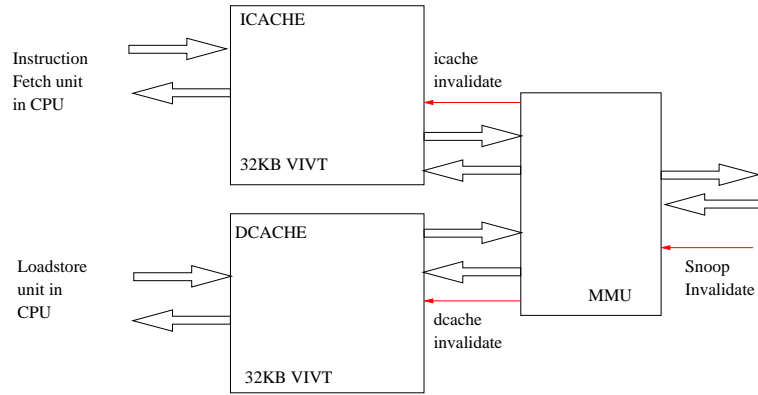


Figure 5.1: AJIT Memory Unit

which keeps track of recently accessed pages which are known to be non-cacheable.

5.2 The AJIT Instruction Cache

The AJIT instruction cache (ICACHE) is a pipelined implementation which supports precise exceptions. The ICACHE has a cache line size of 64 bytes, and is nominally configured to a size of 32KB, although it can be scaled to sizes down to 4KB.

Two implementations of the ICACHE are available:

- A direct-mapped write-through-allocate virtually-indexed-virtually-tagged (VIVT) cache. The direct mapped version has a hit latency of two clock cycles.
- A 2-way/4-way/8-way set-associative write-through-allocate virtually-indexed-virtually-tagged (VIVT) cache. The set associative version has a hit latency of either two or three clock cycles. On average, the set associative version has a hit latency which is 3% higher than the direct mapped version.

5.3 The AJIT Memory Management Unit (MMU)

The SPARC reference MMU is implemented. The MMU contains four distinct TLB's as shown below:

2-entry	Level-0 TLB
4-entry	Level-1 TLB
16-entry	Level-2 TLB
256-entry	Level-3 TLB

The following ASI's are required to be supported, and are in fact supported.

ASI	Description

0x3	MMU-flush-probe flush => whole MMU TLB is flushed probe => only entire probes are supported.
0x4	MMU-register-access
0x8	User-instruction-fetch
0x9	Supervisor-instruction-fetch
0xa	User-data-access
0xb	Supervisor-data-access
0x20-0x2f	MMU bypass
0x30	MMU bypass (reserved for future use)

Bit 8 of the MMU control register is used to encode a default cacheable bit. When the MMU is disabled, bit-8 is passed to the caches as the cacheable bit for the fetched line. This allows the caches to be used even when the MMU is disabled.

Note that the use of this cacheable bit is not standard. The standard behaviour as specified by the SPARC V8 SRMMU specification is that when the MMU is disabled, all accesses are marked non-cacheable. The non-standard extension allows us to disable the MMU functionality while maintaining the use of the caches. Such a capability is useful in evaluating a system which excludes the MMU entirely.

5.4 The AJIT Level-2 Cache

The AJIT level-2 is a physically indexed, physically tagged, 8-way set associative, write-back cache that can be configured for sizes of 64KB to 1MB. The L2 cache has a line size of 64 bytes.

The L2 cache can be used in a flexible manner for assembling AJIT processor systems.

Chapter 6

AJIT processor interfaces

The primary interfaces between the AJIT processor and the external world are:

- AJIT CORE BUS interface (ACB): A 64-bit data, 36-bit address system memory interface.
- AJIT FIFO BUS interface (AFB): A 32-bit data, 36-bit peripheral/memory interface.

Simple bridges between AFB and AHB, AFB and APB are also available.

6.1 AJIT core bus interface

This consists of a request FIFO and a response FIFO. The requester (AJIT processor) writes a request word into the request FIFO. The 110-bit request word has the following format:

bit-field	meaning
[109]	lock
[108]	read/write_bar
[107:100]	byte mask
[99:64]	address
[63:0]	write-data

The response FIFO consists of a 65-bit word with the following format:

bit-field	meaning
[64]	error
[63:0]	read-data

The request/response pair can be used with a pipelined memory.

6.2 AJIT FIFO bus interface

This also consists of a request FIFO and a response FIFO. The requester (AJIT processor) writes a request word into the request FIFO. The 74-bit request word has the following format:

bit-field	meaning
[73]	lock
[72]	read/write_bar
[71:68]	byte mask
[67:32]	address
[31:0]	write-data

The response FIFO consists of a 33-bit word with the following format:

bit-field	meaning
[32]	error
[31:0]	read-data

The request/response pair can be used with a pipelined memory.

6.3 ACB/AFB Protocol and Timing

Both the ACB and AFB schemes are similar in their timing. We illustrate the timing based on the setup described in Figure 6.1.

1. The master initiates a transaction by sending request data to the slave. Thus, the first transfer in a transaction is a request word (110 bits for ACB, 74 bits for AFB) which is transferred from the master to the slave.
2. After the slave has computed the response to the request, the slave sends response data to the master. Thus, the second transfer is response word (65 bits for ACB, 33 bits for AFB) which is sent to the master.

The protocol and protocol for each transfer is similar and is described below.

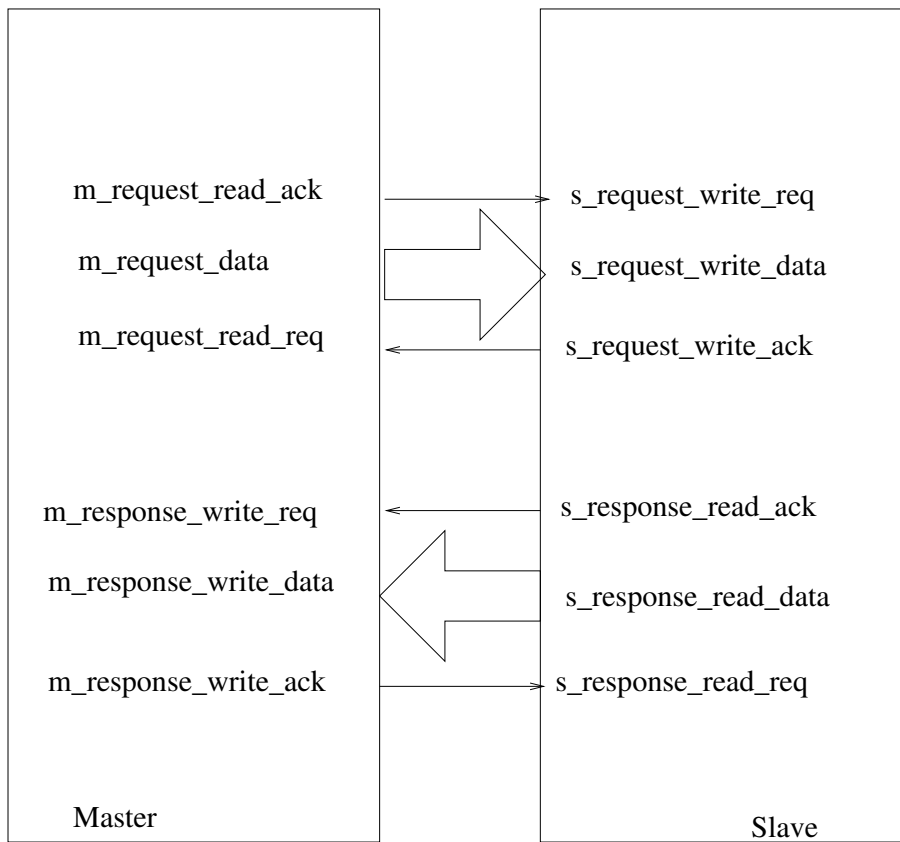


Figure 6.1: Visualization of setup for ACB/AFB master slave connections

6.3.1 Timing of a single transfer

The protocol relies to two wires between the sender and receiver.

- The first wire goes from the sender to the receiver. On the sender side, this wire is interpreted as *sender has data to send*. This wire connects to the receiver's write_req port and the senders read_ack port.
- The second wire goes from the receiver to the sender. On the receiver side, this wire is interpreted as *receiver ready to receive*. This wire connects to the sender's read_req port and to the receiver's write_ack port.

Now the behaviour of the sender can be summarized as follows:

```
sender_has_data_to_send = 0
if (sender wants to send) {
    sender_data = DATA,
    sender_has_data_to_send = 1
    while(1) {
        if (receiver_ready_to_receive)
            break; /* receiver has accepted */
    }
}
```

The behaviour of the receiver can be summarized as follows:

```
receiver_ready_to_receive = 0
if (receiver wants to receive) {
    receiver_ready_to_receive = 1
    while(1) {
        if (sender_has_data_to_send)
            REGISTER = sender_data
            break; /* receiver has accepted */
    }
}
```

This protocol is highly flexible and allows either the sender or receiver to block the transaction. For example, if the sender is faster than the receiver, the timing diagram will be as shown in Figure 6.2. If the receiver is faster than the sender, the timing diagram will be as shown in Figure 6.3. If both sender and receiver are full-rate, then the timing diagram will be as shown in Figure 6.4.

6.4 Bridges

Bridges are available between the AJIT interface busses and industry standard busses as follows:

- ACB to AFB bridge.

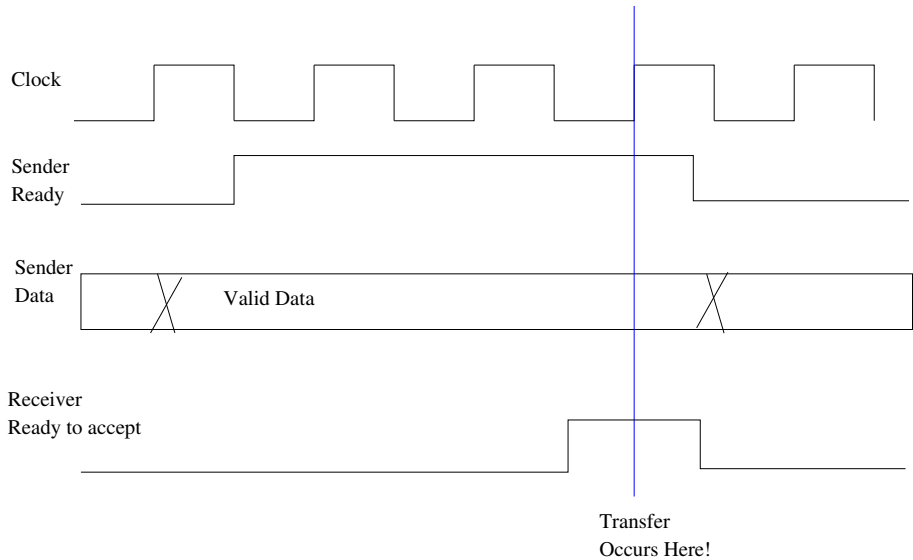


Figure 6.2: Timing Diagram for fast sender, slow receiver

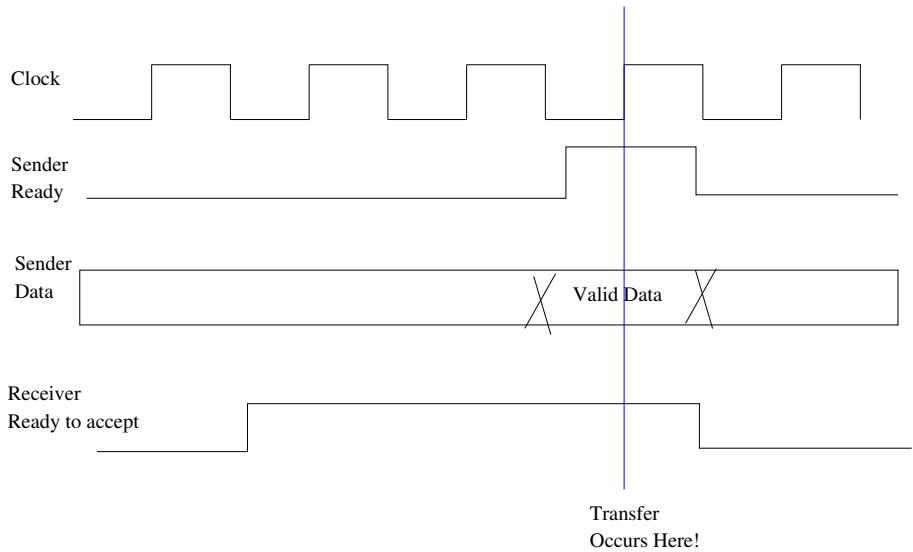


Figure 6.3: Timing Diagram for slow sender, fast receiver

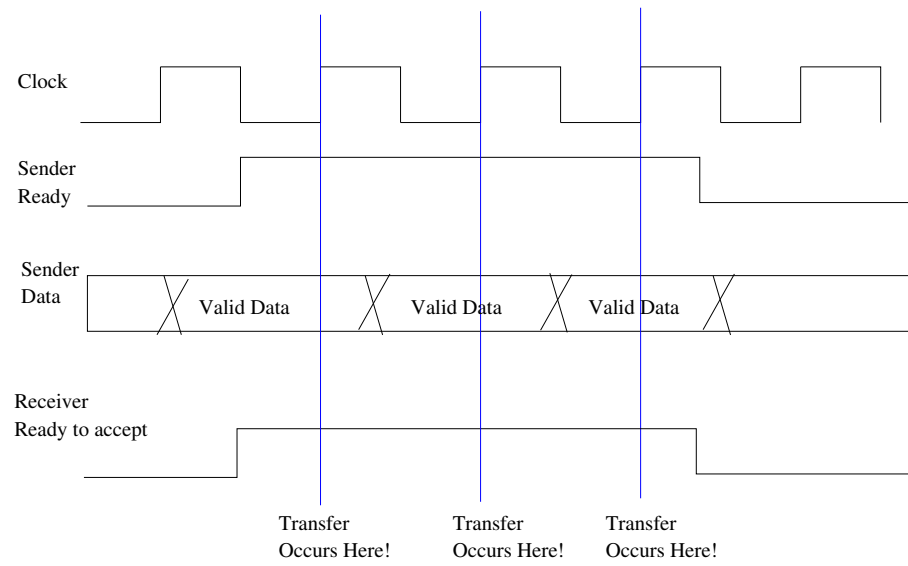


Figure 6.4: Timing Diagram for full-rate sender and receiver

- AFB to AHB bridge.
- AFB to AXI/AXI-lite bridge.
- AFB to APB bridge.

Chapter 7

Basic peripherals available for AJIT systems

Basic peripherals that can be used in the FPGA are available. These include: a timer, a UART, an interrupt controller, an SPI flash controller, an I2C master, an SPI master.

7.1 The AJIT multi-core interrupt controller

The AJIT multi-core interrupt controller is a collection of eight thread interrupt controllers (TIC). Each thread interrupt controller corresponds to an active CPU thread in the AJIT multi-core system, and is identified by a (core_id, thread_id) pair, where core_id is either 0/1/2/3 and thread_id is 0/1. With the TIC complex, it is possible to dynamically map interrupts to threads, with complete flexibility.

7.1.1 Registers and their memory mapping

Each TIC has one register assigned to it. The addresses of these registers are as follows:

core-id	thread-id	register-address

0	0	BASE
0	1	BASE + 0x4
1	0	BASE + 0x8
1	1	BASE + 0xc
2	0	BASE + 0x10
2	1	BASE + 0x14
2	0	BASE + 0x18
2	1	BASE + 0x1c

The control register for each TIC has the following format

```
[31:17] interrupt vector (which interrupts are currently active?)
[16]      unused
[15:1]   interrupt mask (if bit is set, the interrupt is recognized)
[0]      enabled
```

7.1.2 TIC state machines

Each TIC follows a state machine with the following states.

```
IRC_DISABLED
IRC_ENABLED
IRC_INTERRUPTING
```

The state transitions are described by the following state machine:

- On reset:

```
state := IRC\_DISABLED
control_reg := 0
```

- When state is IRC_DISABLED: if there is a write to the control register with [0] = '1' then move to IRC_ENABLED. Else stay here.
- When state is IRC_ENABLED: if an unmasked interrupt is active, then move to IRC_INTERRUPTING else if there is a write to control register with bit 0 = 0, then move to IRC_DISABLED.
- When state is IRC_INTERRUPTING: encode the active unmasked interrupt to the interrupt level for the corresponding thread (INTR_LEVEL_icode_id_ithread-id_i). If there is a write to control register with bit 0 = 0, then move to IRC_DISABLED.

Thus, each TIC goes through the state sequence

```
IRC_DISABLED -> IRC_ENABLED -> IRC_INTERRUPTING -> IRC_DISABLED
```

7.1.3 VHDL

```
entity afb_multicore_interrupt_controller
Described in      GlueModules.vhdl
compile into library GlueModules
```


7.2 The default count-down timer

The timer is a memory mapped device with a CPU-side interface that consists of request/addr/write-data input-pipes and a read-data output pipe.

It generates a single output interrupt which connects to the interrupt controller.

The timer has a single memory mapped 32-bit control register which is currently mapped to virtual memory 0xffff3100. The control register fields are:

```

31:1    max-timer-count.
0       enable bit
        when set, the timer does a count-down from the
        max-timer-count and when the count reaches 0,
        asserts the interrupt.

```

Its behaviour is as follows:

- Starts in disabled state. When control-reg-bit 0 is set, it moves to the enabled state, and starts the count-down-timer.
- Stays in the enabled state until the count reaches 0, after which the timer moves to the interrupting state in which the timer interrupt is asserted (held) to the system constant `TIMER_IRL` which has value 0xa.
- The timer stays in the interrupting state until the CPU either explicitly enables the timer (moves to enabled state) or disables the timer (moves to disabled state).
- If at any point, the CPU enables/disables the timer (by doing a register write), the timer will immediately move to either the enabled/disabled state and perform the appropriate actions.

7.2.1 VHDL

```

entity afb_timer
Described in      GlueModules.vhdl
compile into library GlueModules

```

7.3 The simple serial device

The serial device is a memory mapped I/O device that allows for exchange of bytes between the CPU and an external I/O device such as a UART. It is assigned an interrupt level of 12.

The serial device has three internal registers

- an 8-bit rx_register into which data read from the input pipe is stored (this is mapped to address 0xffff3220).

- an 8-bit tx_register into which data from the CPU is written (mapped to address 0xffff3210).
- a 5-bit control/status register (mapped to address 0xffff3200) which has the following bit-fields

4: rx-register-full.

if set indicates that the rx-register has data that needs to be read. The rx-register will not be updated until data has been read by the CPU.

NOTE: writes to the control register will not modify this bit. The bit is set when data is written into the rx-register. The bit is cleared when the rx-register is read.

3: tx-register-full.

if set indicates that the tx-register has been updated by the CPU but has not yet been transmitted.

NOTE: writes to the control register will not modify this bit. The bit is set when data is written into the tx-register. The bit is cleared when the tx-register is transmitted.

2: rx-interrupt-enable.

if set indicates that an interrupt should be raised whenever the rx-register has been updated.

1: rx-enable

if set (by the CPU) indicates that the receive function is active.

0: tx-enable

if set (by the CPU) indicates that the transmit function is active.

- Two registers for setting the baud rate.

register	address
-----	-----
baud-limit-register	0xffff320c
baud-frequency-register	0xffff3210
-----	-----

These registers are set by the

`__ajit_serial_set_baudrate__`

function provided as part of the AJIT access routines (see Chapter ??).

Internally, its behaviour is modeled by two state machines, the rx and tx state machines.

The rx state machine starts in idle. If rx-enable is set, it moves to an enabled state. In the enabled state, it looks to read from the input pipe and if data is read, moves to the received state (and if rx-interrupt-enable is set, raises an interrupt). It stays in the received state until the rx-register is read by the CPU, at which point it moves to either disabled/enabled state as indicated by the rx-enable bit.

The tx state machine starts in idle. If tx-enable is set, it moves to an enabled state. In the enabled state, it waits for a tx-register write from the CPU, and when this happens, it moves to the transmit state, and sets tx-full to 1. In the transmit state, it writes the tx-register to an internal pipe to a transmit daemon, and goes to a transmit-done-wait state. In this state, when it receives an OK from the transmit daemon, it clears tx-full = 0, and moves to either disabled/enabled state as indicated by the tx-enable bit.

7.3.1 Using the serial device: RX

To use the serial device on the RX side, the cpu must enable the rx function. The serial device will then attempt to read a byte into the rx-buffer. If the cpu has also enabled the rx-interrupt function, an interrupt is generated when the byte is read into the rx-buffer. The rx-full flag is also asserted. When the CPU reads the rx-buffer, the rx-full flag is deasserted and the rx state goes back to enable. Thus, the CPU should use the RX in the following ways

```
rx-enable ->
  poll-rx-full ->
    read-rx-register ->
      disable (or leave enabled).

rx-enable ->
  wait-intr ->
    read-rx-register ->
      disable (or leave enabled).
```

7.3.2 Using the serial device: TX

To use the serial device on the TX side, the cpu must enable the tx function. When the cpu writes to the tx-buffer, the serial device sets tx-full, and will attempt to write the byte out, and when it succeeds, will clear tx-full. The cpu should monitor tx-full and if it is empty, disable the tx function.

```
tx-enable ->
  write-tx-buf ->
    poll-tx-full ->
      disable.
```

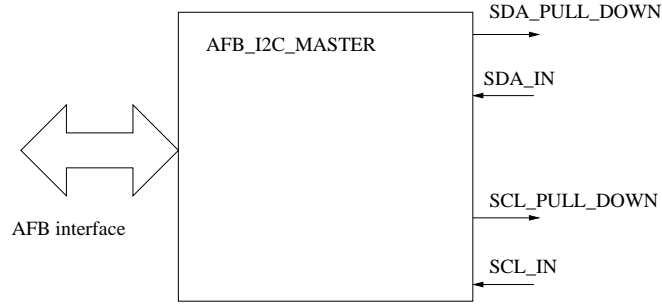


Figure 7.1: AFB SPI Flash controller

7.3.3 Restrictions on accesses to the serial registers

The serial control register **must** be accessed by single word load/stores (**st** and **ld** instructions). However, the Tx and Rx registers **must** be accessed by byte load/store instructions (**ldub** and **sturb**).

7.3.4 VHDL

```
entity afb_serial_adapter
Described in      GlueModules.vhdl
compile into library GlueModules
```

7.4 AFB I2C master controller

This provides an interface from the AFB bus (AJIT peripheral bus) to an I2C master. The block diagram is shown in Figure 7.1.

There are three addressable registers in the I2C master.

name	address offset	contents
register-0	0x0	[31:0] = clock divider count.
register-1	0x4	[31:0] = command register
register-2	0x8	[31:0] = response register.

All registers must be accessed as 32-bit wide word accesses.

The clock divider count can be programmed by the user. If the clock frequency to the I2C master is X, and the desired I2C frequency is Y, then the clock divide count should be set to

$$(X/Y)/4$$

The command register has the following format:

```

[31]    rwbar
[30:29] write-mask
        [30] if set send register address
        [29] if set send write data.
[28:22] unused
[22:16] device address
[15:8]  register address in device.
[7:0]   write data byte.

```

The write-mask bits determine which bytes are sent to the I2C bus. For an I2C device register access, bits [30:29] are set 11. But it is possible to send just the register address by using 10, and just the write data byte by using 01.

The response register has the format

```

response format: [31:11] unused
                  [10]  ready
                  [9]   ack-error
                  [8]   busy
                  [7:0] read data

```

The user of the I2C master is expected to poll the response to determine if the master is ready or busy, and reads back the value received from the I2C slave device from the read data field. An error bit is also provided.

7.4.1 VHDL

```

entity          afb_i2c_master
Described in file simpleI2CLib.vhdl
Library         simpleI2CLib

```

7.5 Self Tuning UART

A self tuning UART will use an initial received byte (value 0x80) sent from the external calibrator to estimate the clock ticks per baud.

Subsequent to the initial byte, the UART will function normally.

The VHDL entity for the self-tuning UART is `mySelfTuningUart`, compiled into library `myUartLib`. After reset, the calibrator will be required to transmit 0x80 to the UART.

The ports of the self-tuning UART are

```

entity mySelfTuningUart is
  port (
    -- rising edge of clock is used, reset is active high.
    clk, reset: in std_logic;
    -- Rx, Tx

```

```

    UART_RX: in std_logic_vector(0 downto 0);
    UART_TX: out std_logic_vector(0 downto 0);
    -- Fifo interface to user logic (user logic writes
    --    into FIFO TX_to_CONSOLE)
    TX_to_CONSOLE_pipe_write_data: in std_logic_vector(7 downto 0);
    TX_to_CONSOLE_pipe_write_req:  in std_logic_vector(0 downto 0);
    TX_to_CONSOLE_pipe_write_ack:  out std_logic_vector(0 downto 0);
    -- Fifo interface to user logic (user logic reads
    --    from FIFO CONSOLE_to_RX)
    CONSOLE_to_RX_pipe_read_data : out std_logic_vector(7 downto 0);
    CONSOLE_to_RX_pipe_read_req  : in std_logic_vector(0 downto 0);
    CONSOLE_to_RX_pipe_read_ack  : out std_logic_vector(0 downto 0));
end entity mySelfTuningUart;

```

The calibration sequence is as follows:

- Reset the UART
- Write 0x80 into the UART to calibrate, using the calibrate routine (see below).
- Wait 1ms.
- Start normal use of the UART.

A utility routine `calibrateUart` is provided to do the calibration. From the terminal, type

```
calibrateUart /dev/ttyUSBx
```

where USBx is the tty corresponding to your UART.

7.5.1 VHDL

```

entity mySelfTuningUart
Described in      myUartLib.vhdl
Compiled into library myUartLib

```

7.6 AFB SPI Master

The AFB SPI master provides SPI master functionality with an AFB interface. Using the AFB bus, it is possible to address four internal registers to achieve the SPI master function. The structure of the AFB SPI master is shown in Figure 7.2. The SPI-master implementation is based on an implementation by Hans Huebner (Copyright 2009-2010) from opencores.org.

The internal registers are addressed using the bottom two bits of the AFB address as follows:

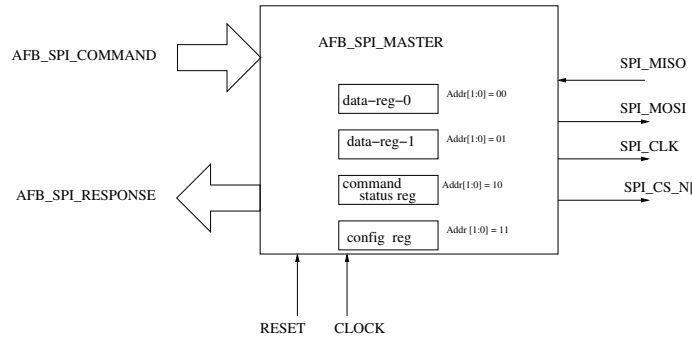


Figure 7.2: AFB SPI master

addr	register
00	data-reg-0[7:0] (data_low)
01	data-reg-1[15:8] (data_high)
10	Command/status
11	Config

The two registers data-reg-1 and data-reg-0 form a shift register of length 16. Serial data out from the SPI master (MOSI) is tapped out from either at half-word (16-bit) or 12/8/4 bit points along the shift register. Incoming bits go into data-reg-0[0].

When a byte is written to the command/status register, it is interpreted as follows (bit-fields):

[7:6]	unused
[5:3]	SPI slave address
[2]	IRQ-en
[1]	Deselect after transfer
[0]	start-transfer

When a byte is read from the command/status register, it provides the following information

[7:1]	unused
[0]	busy

The busy bit is set to indicate that a transfer is ongoing.

When a byte is written to the config register, it is interpreted as follows:

[5:4]	transfer-length
	00=4 bits, 01=8 bits
	10=12 bits, 11=16 bits
[3:0]	clock-divide count
	0000=clk/2, 0001=clk/4 etc.
	upto 1111=clk/131072.

The SPI-CLOCK is obtained by dividing the system clock by

$$2^{clkdividecount+1}$$

The default is divide by 8. The transfer length coding is

```
00    4-bits
01    8-bits  (default)
10   12-bits
11   16-bits
```

To transmit a byte using the SPI-master, we go through the following sequence:

- Configure the SPI clock, transfer length.
- Wait until the master is free (check busy bit of status register to check).
- Write a byte into data register.
- Write a command to the command register to initiate the transfer.
- The clearing of the busy bit in the status register indicates end of transfer. An interrupt can also be generated.

To receive a byte using the SPI-master.

- Wait until the master is free (not busy).
- Write command to CS to initiate the transfer.
- Wait until master is free.
- Read the data buffer(s).

7.6.1 VHDL details

The details of the VHDL implementation of the AFB SPI master are as follows:

```
entity          afb_spi_master
Described in file GenericCoreAddOnLib.vhdl
library        GenericCodeAddOnLib
```

7.7 AFB SPI Flash controller

This controller provides a simple AFB interface to a serial SPI Flash memory such as the ones on the Kintex 705 FPGA cards from Xilinx (See Xilinx documentation note XAPP586 from www.xilinx.com). The AFB SPI Flash controller provides read-write access to serial (SPI) flash memory. Alternate resources on an FPGA card can be used to write to the flash memory. With

this controller, the flash memory can be accessed using the normal AFB request response protocol.

The AFB SPI flash controller will serve the memory request specified on the AFB request using an SPI Flash device. Currently, SPI flash devices from Micron have been validated. The SPI flash device must have a capacity between 128KB (1 Mbit) and 16 KB (128 Mbit).

The WRITE_PROTECT input on the AFB SPI flash controller is used as follows:

- When WRITE_PROTECT is tied to '1', then all writes to the flash controller are ignored.
- When WRITE_PROTECT is tied to '0', the flash controller will serve writes. Further, the first write after reset also triggers an ERASE operation in the flash device, which initializes all storage bits in the flash to '1', ready to be written. This erase operation can take several seconds to complete.

7.7.1 VHDL

The AFB SPI Flash read/write controller VHDL details are listed below:

```
entity afb_flash_rw_controller
described in VHDL file  GlueModules.vhdl
compile into library    GlueModules
```

7.8 Processor core add-ons

There are some useful building blocks which can help you put together a system using the generic AJIT processor core. We describe these add-ons briefly.

7.8.1 GlueModules

The file GlueModules.vhdl contains several important building blocks, summarized below:

```
-----
GlueModules.vhdl
-----

acb_afb_bridge
  ACB to AFB bridge, will convert 64-bit
  ACB bus to 32-bit AFB bus.

acb_fast_mux
  ACB request/response multiplexor.
```

66CHAPTER 7. BASIC PERIPHERALS AVAILABLE FOR AJIT SYSTEMS

`acb_fast_splitter`
ACB splitter with 0-delay

`acb_fast_tap`
ACB fast tap with 0-delay

`acb_null_stub`
ACB null device, returns zero response

`afb_acb_bridge`
AFB to ACB bridge.

`afb_fast_mux`
ACB request/response multiplexor.

`afb_fast_splitter`
AFB fast splitter with 0-delay

`afb_fast_tap`
AFB fast tap with 0-delay

`afb_flash_rw_controller` (read/write)
flash read-write controller, interfaces to
AFB bus and to SPI flash with sizes in
range 128KB to 16MB.

`afb_multicore_interrupt_controller`
interrupt controller.

`afb_null_stub`
AFB null device, returns zero response

`afb_scratch_pad`
AFB compatible 32x32 scratchpad.

`afb_serial_adapter`
AFB serial adapter.. Need to connect
this to UART for complete functionality.

`afb_timer`
AFB timer.

`afb_trace_logger`
AFB trace logger.

7.8.2 GenericCoreAddOnLib

The file GenericCoreAddOnLib.vhdl contains more useful building blocks.

`ahblite_controller`
AHB controller.

`afb_ahb_bridge`
AFB - AHB bridge

`afb_apb_controller`
AFB - APB bridge.

`acb_sram_stub`
ACB SRAM

`afb_sram_stub`
AFB SRAM

`afb_2port_sram_stub`
AFB dual-ported SRAM

`afb_splitter`
AFB splitter (slower than the fast splitter
in GlueModules, deprecated).

`ahb_sram_stub`
AHB SRAM

`apb_sram_stub`
APB SRAM

`afb_spi_bridge`
AFB to SPI bridge

`afb_spi_master`
AFB SPI master.

`afb_spi_flash_controller` (read-only)
flash read-only controller, interfaces to
AFB bus and to SPI flash with sizes in
range 128KB to 16MB.

`afb_gpio`
32-bit GPIO

`afb_mux`

68CHAPTER 7. BASIC PERIPHERALS AVAILABLE FOR AJIT SYSTEMS

AFB multiplexor

Chapter 8

AJIT access routines and support utilities

In order to program systems using the AJIT processor, several utilities are provided. These routines are kept in the AJIT tool-chain area in the following locations:

```
AjitPublicResources
    ajit_access_routines_mt
        include
        src
        asm

    minimal_printf_timer
        include
        src
```

The AJIT access routines consist of hardware access functions, and peripheral access functions. For more information, see

```
AjitPublicResources
    ajit_access_routines_mt
        include/ajit_access_routines.h
```

8.1 Trap handlers and interrupt handlers

In the directory

```
AjitPublicResources
    ajit_access_routines_mt
        asm
```

there are several important assembly routines which are essential for applications. These include

- Trap handlers:

```
trap_handlers_for_rtos.s
    window-overflow/underflow trap-handlers.
```

- Interrupt service routines:

```
generic_isr_single_stack_mt.s
    generic isr which runs on the same
    stack as the interrupted task.
```

```
generic_isr_with_separate_stack_mt.s
    generic isr which uses a separate
    stack from the interrupted task.
```

- Mutexes:

```
mutexes.s
    mutex using swap instruction
    and using ldstub instruction.
```

- Software trap handlers:

```
generic_sw_trap_mt.s
    generic software trap handler.
```

- System calls:

```
generic_sys_calls.s
    system-call implementations.
```

Chapter 9

AJIT Development Tools

We describe the important development tools that are required for embedded system design and debug around the AJIT processor cores.

9.1 The AJIT Debug Monitor

The AJIT debug monitor utility uses the hardware debug interface unit in the AJIT processor in order to control execution in a system which uses the AJIT processor core.

The setup of the debug monitor utility is shown below.

```
-----  
ajit_debug_monitor_mt  <--- uart --->  AJIT multi-threaded  
    runs on PC                               FPGA prototype  
-----
```

9.1.1 Synopsys

The AJIT debug monitor utility is invoked at the command line.

```
ajit_debug_monitor_mt -u <tty-dev> [-n <ncores>] [-t <nthreads-per-core>]
```

The options are

```
-u tty-dev required, when the processor core is  
    mapped to an FPGA board, with a serial UART (tty-dev)  
    being used as the debug connection.  
-n <ncores> , optional, specify number of cores  
    (default = 1, maximum = 4)  
-t <nthreads_per_core> , optional, specify number of threads  
    in each core (default = 1, maximum = 2)
```

The AJIT debug monitor provides the user with a command shell for an interpreter. The command prompt is

```
ajit[0:0]>
```

The two numbers 0 : 0 in the prompt specify the core and thread id which is currently being controlled/observed in the monitor. To change the core and thread being monitored, we can at any time use

```
ajit[0:0]> t 0 1
```

This will change the core and thread id if possible (note the -n and -t options above). The prompt now changes to

```
ajit[0:1]>
```

For each prompt, the user can supply a command. The commands are classified as follows:

```
Reset/mode control/observe.
Initial PC/NPC/PSR control/observe.
State register control/observe.
Integer general purpose register observe/control.
Floating-point general purpose register observe/control.
Memory control/observe.
Load memory map file.
Run script file.
Start/stop GDB server.
Help, quit, log.
```

9.1.2 Reset/mode control/observe

Using the interpreter, it is possible to control the reset values applied to the core, as well as to observe the mode it is running in.

```
w rst <reset-val>
Write reset-val to the 4-bit CPU reset input to
the AJIT core. The value must be an integer value,
specified either using the hex (0x...) or decimal format.
```

The command

```
w rst 0x1
```

puts the processor in reset mode, and

```
w rst 0x0
```

brings it out of reset.

The “rst” value is a 4-bit field, with the bit-fields being interpreted as follows:

- [3] : if set, the processor will produce a logging trace (this is reserved, and may not be supported in your platform).
- [2] : if set, the processor will run in single-step mode.
- [1] : if set, connect to debugger before executing first instruction, after reset is released
- [0] : if set, initialize the CPU, Caches, MMU. This must be cleared to start running code.

The following commands

```
r mode
```

reads the CPU mode. This is a 4-bit value, and should have one of the following values

value	meaning
0x0	uninitialized mode
0x9	in reset mode.
0x2	in normal run mode.
0x3	in error mode.

Note that the processor core will stay in reset mode as long as the least significant bit of the controlled rst value is 1.

9.1.3 Initial PC/NPC/PSR control/observe

We can set the initial value of PC, NPC, PSR so that the processor starts (post-reset-release) from the desired instruction and status register state.

```
w ipc <init-pc-val>
```

sets the initial PC at which the processor core starts when it comes out of reset. For example

```
w ipc 0x40000000
```

means that when the CPU comes out of reset, the initial PC is 0x40000000.

```
r ipc
```

returns the value of initial PC.

Similarly, one can set/observe the value of the initial NPC, and initial PSR values for the processor thread being monitored.

```
w inpc <init-npc-val>
r inpc
w ipsr <init-psr-val>
r ipsr
```

9.1.4 State register control/observe

It is possible to control and observe the current value of the state registers using the interpreter.

```
w psr/wim/tbr/y <hex-value>
```

sets the current value of one of PSR/WIM/TBR/Y registers to the specified hex-value. For example

```
w wim 0x1
```

sets the WIM value in the processor thread to 0x1. To observe the status registers, one can use

```
r psr/wim/tbr/y
```

to read the current value of PSR/WIM/TBR/Y registers in the processor thread. returns the current value of the TBR.

Ancillary state registers can be accessed using

```
w asr <asr-id> <asr-value>
```

e.g.

```
w asr 0x1 0xff
sets the value of ASR[0x1]
to 0xff.
```

```
r asr <asr-id>
```

e.g..

```
r asr 0x1
returns the current value of ASR[0x1].
```

9.1.5 Integer general purpose register control/observe commands

It is possible to observe control/observe the general purpose register values using the interpreter.

```
w iureg <reg-id> <reg-value>
```

e.g.

```
w iureg 0x7 0xff
sets the value of R[0x7] to 0xff.
```

```
r iureg <reg-id>
```

e.g..

```
r iureg 0xf
returns the current value of R[0xf].
```

9.1.6 Floating point general purpose register control/observe commands

It is possible to observe control/observe the floating point register values using the interpreter.

```
w fpreg <reg-id> <reg-value>
  e.g.
    w fpreg 0x7  0x10000000
    sets the value of F[0x7] to 0x10000000.

r fpreg <reg-id>
  e.g.
    r fpreg 0xf
    returns the current value of F[0xf].
```

9.1.7 Memory control/observe commands

It is possible to observe control/observe any memory location using the interpreter (including the various supported ASI's). Observation and control is possible at the word (32-bit) level only.

```
w mem <asi-value> <addr-value> <write-value>
  write 32-bit write-value to address addr-value in
  the memory space defined by asi asi-value. Address is
  force aligned to 32-bit access by setting bottom
  two bits to 0.

  e.g.
    w mem 0xa  0x0 0xffffffff
    sets the value of mem[0x0] with asi=0xa to 0xffffffff.

r mem <asi-value> <addr-value>
  Read the current 32-bit value of the memory
  (identified by asi) location addr-value.

  e.g.
    r mem 0xa 0x0
    returns the current value of mem[0x0],
    with memory defined by asi=asi-value.
```

9.1.8 Load memory map file

It is possible to load a memory map into system memory by using the interpreter. The memory map file consists of byte-address, byte-value pairs, both specified in hex format.

```
m <mmap-file>
    load the memory map in mmap-file to the processor
    memory.
```

9.1.9 Execute script file

A list of debug monitor commands can be listed in a file, and the file can be executed as a script. Comment lines in the script start with a "!" character.

```
s <script-file>
    execute the AJIT debug monitor commands listed in the script-file.

e.g. script file
! Comment: reset the core..
w rst 0x1
! load mmap file.
m mmap.txt
! bring core out of reset.
w rst 0x0
! read mode
r mode
```

9.1.10 Start/stop GDB server

The AJIT debug monitor can start a GDB debug server on the host machine to allow GDB to remotely connect to the current thread and control a debugging session. Note that the GDB connection and the AJIT debug monitor use the same connection to communicate with the host. Thus, when GDB is active, the debug monitor should be quiet.

```
g start <port-id>
    Start the GDB server to listen on port port-id.
g stop
    Stop the GDB server.
```

9.1.11 Help, quit, log

These are useful commands to get basic online help, to quit the interpreter, and to generate a command log for re-use.

```
q
    quit the monitor.

h
    print a help message.

l <log-file>
```

```
generate a log of successful commands
into log-file.
```

9.1.12 Use Scenario

The processor+system must be mapped to an FPGA card, with the debug interface being mapped to a UART. The reset switch inputs to the processor on the FPGA card must be 0. Further the AJIT tool chain must be set up on the host machine.

Suppose we are monitoring a one core, four thread processor. In typical use, one follows the sequence (script file shown below):

```
! put the thread (0,0) in reset
w rst 0x1
! set initial values for pc/npc/psr in thread (0,0).
w ipc 0x0
w inpc 0x4
w ipsr 0x10c0
! put the thread (0,1) in reset
t 0 1
w rst 0x1
! set the initial values for pc/npc/psr in thread (0,1)
w ipc 0x0
w inpc 0x4
w ipsr 0x10c0
! download the memory map (m <mmap-file>)
m ADD.mmap
! release the reset for the current thread 0 1
w rst 0x0
! change thread to 0 0
t 0 0
! release the reset for the current thread 0 0
w rst 0x0
```

Now both threads are running and you can monitor their modes.

```
r mode
t 0 1
r mode
.. etc ..
! quit
q
```

You can start a GDB server through the debug monitor. The debug monitor and GDB server use the same connection to the processor. Thus, once you start a GDB server, you cannot resume normal debug monitor activity.

The following sequence must be followed to debug a 1-core two thread system using GDB.

```

! put thread 0 0 in reset mode
w rst 0x1
! set initial values for pc/npc/psr for thread 0 0
w ipc 0x0
w inpc 0x4
w ipsr 0x10c0
! put thread 0 1 in reset mode.
t 0 1
w rst 0x1
! set initial values for pc/npc/psr for thread 0 1
w ipc 0x0
w inpc 0x4
w ipsr 0x10c0
! download the memory map (m <mmmap-file>)
m ADD.mmap
! start GDB server on port 8889 for thread 0 1
g start 8889
! change thread to 0 0
t 0 0
! start GDB server on port 8888 for thread 0 0
g start 8888
! bring thread 0 0 out of reset, but in debug-mode
w rst 0x2
! change to thread 0 1
t 0 1
! bring thread 0 1 out of reset, but in debug-mode
w rst 0x2
!
! From here on, the debug monitor should
! be quiet until the debugging session is
! over. Two GDB clients will be needed
! to connect to the two GDB servers started
! above..
.. eventually ...
q

```

Note that at the end of the GDB session, you need to quit the debug monitor.

9.2 Processor models: C reference ISA model

The first processor simulation model is a C reference models, which can be thought of as a processor emulator. This models the instruction set architecture, the Caches, the MMU and the main memory.

ajit_C_system_model

This is a reference C model of the processor, together with a 32kB direct mapped write through DCACHE, a 32 kB direct mapped ICACHE, an MMU and a main memory. A serial device, timer and interrupt controller are also modeled. It is possible to load the memory with initial contents. The model resets the processor to start from PC=0x0, and runs until the processor enters error state.

During the execution of the model, it is possible to connect a debugger (gdb), set break and watch points and monitor contents of registers/memory in the processor model.

It is also possible to define a post-condition on the register and memory contents and to confirm that the values in the registers/memory are consistent with the expected values. This post condition is checked after the processor has reached the error state.

The principal options for this tool are:

`-m <mmap-file>`

required, specifies memory-map of processor for this test.

`[-n <number-of-cores>]`

Optional.

The number of cores to be modeled. This number can be between 1 and 4. The default is 1.

(NOTE: In each cpu, asr29 holds the cpu-id which can be 0/1/2/3).

`[-u 32/64]`

Optional.

If `-u 64` is specified, the 64-bit extensions to the Sparc-V8 ISA are also modeled. Otherwise (the default), only Sparc-V8 instructions are decoded and the extensions cause an unimplemented instruction trap.

`[-g]`

Optional, run the CPU in debug mode.

`[-p <gdb-port-number>]`

Required with `-g`, to specify remote debug port.

`[-d]`

Optional, check post-condition.

`[-r <results-file>]`

Required with `-d`, specifies expected register/memory values at end of run (post-condition).

`[-l <log-file>]`

Required with `-d`, specifies a log-file of the post-condition checks.

`[-q <number-of-address-bits>]`

Optional, size of memory is $2^{**\text{<number-of-address-bits>}}$, default is 32.

`[-w <reg-writes-dump>]`

Optional, if specified, a log of all register and memory writes is generated (a separate file is generated for each cpu core).

As an example, you could invoke

```
ajit_C_system_model -m add_test.mmap -n 4\
    -d -l add_test.log -r add_test.results\
    -w add_test.wtrace
```

This uses `add_test.mmap` as the memory map file and uses `add_test.results` as the post-condition. It also generates a write-trace of the executed instructions for each cpu core that is modeled.

Another example:

```
ajit_C_system_model -m add_test.mmap -g -p 8888
```

This loads `add_test.mmap` and waits to connect to a remote debug session via port 8888.

The typical performance of this model is 150K instructions per second per core.

9.3 Compilation tools

The cross-compilation tools `sparc-linux-*` are available. These include the C compiler (`sparc-linux-gcc`), the assembler (`sparc-linux-as`), the linker (`sparc-linux-ld`) and other useful GNU tools for porting code to the AJIT processor.

The compilation flow is shown in Figure 8.1. The components of this flow are declared in more detail below.

9.3.1 compileToSparcUclibc.py

For compiling bare-metal applications to the AJIT core, the following utility is to be used.

```
compileToSparcUclibc.py ... options ...
```

The script generates elf, hex-dump, object-dump and memory-map files, given the source code that is to be compiled, assembled and linked.

The options are as follows

`[-h]`

help message and quit.

`[-W work-area]`

output directory (default `./`)

`[-L linker-script]`

linker directives script file to be used.

`-N` name of the application..

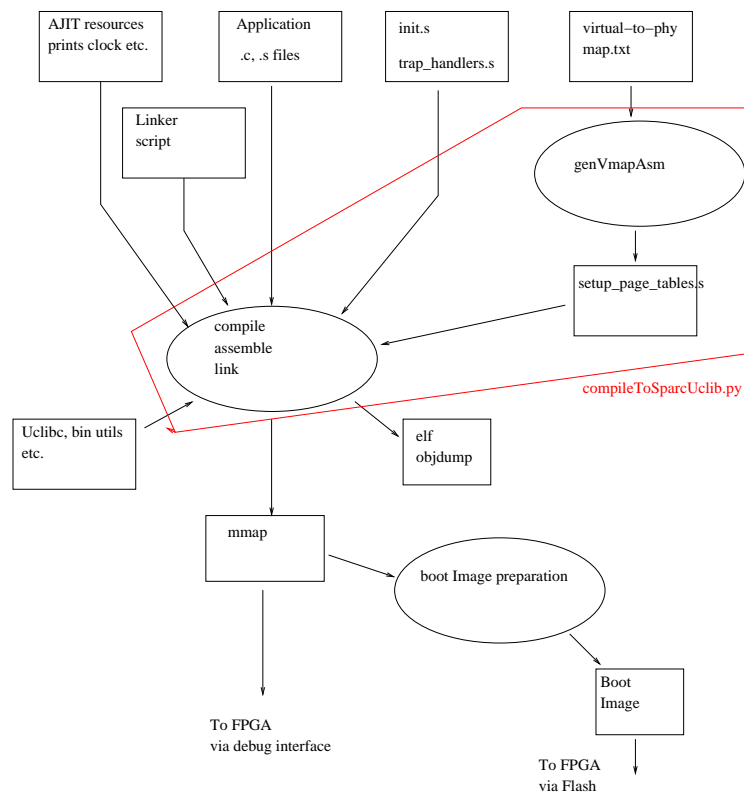


Figure 9.1: Overall compilation flow

If the name is foo, then foo.elf will be generated.

```

-I dir
    include directory (multiple can be specified)
-C dir
    all *.c files in dir will be compiled.
-c file.c
    file.c will be compiled.
-S dir
    all *.s files in dir will be assembled.
-s file.s
    file.s will be assembled.
-D define-string
    define-string will be passed to C compiler
[-U] uclibc flag
    if specified, the final executable links to
    uclibc
[-g]
    C files will be compiled with -g
[-o 0/1/2/3]
    C files will be compiled with -O0/-O1/-O2/-O3
(-F <compiler-option>)*
    You can pass a compiler option.. for example if
    you specify -F frename-registers, then the option
    "-frename-registers" will be passed to the compiler.

```

Thus, it is possible to specify the assembly files, C files, include directories, library directories, defines, linker script, virtual to physical memory map and use these to produce a final executable.

9.3.2 makeLinkerScript.py

You can generate a basic linker script (passed to the compileToSparc.py using the -L option) using the makeLinkerScript.py script. This is used as follows:

makeLinkerScript.py options

The options are as follows

```

(-h)? (print-help message)
(-t <text-section-address>)
    address to start text-segment, default= 0x0
(-d <data-section-address>)
    address to start data-segment, default 0x1000
(-o <output-file-name>)

```

For example, to map data sections to 0x40000000 and higher, and to start the text section at 0x0, use:

```
makeLinkerScript.py -t 0x0 -d 0x40000000 -o customLinkerScript.lnk
```

This produces the following linker script.

```
/* Linker script generated for AJIT standalone application */
/* command: makeLinkerScript.py -t 0x0 -d 0x40000000 -o customLinkerScript.lnk */
ENTRY (_start)
__DYNAMIC = 0;
SECTIONS
{
    . = 0x0;
    .text ALIGN(4) : {
        KEEP(*(.text.ajitstart))
        KEEP(*(.text.pagetablesetup))
        KEEP(*(.text.traphandlers))
        KEEP(*(.text.traptablebase))
        *(.text) *(.text.*) }
    . = 0x40000000;
    .rodata ALIGN(4) : { *(.rodata) *(.rodata.*) }
    .data ALIGN(4) : { *(.data) *(.data.*) *(.bss)}
}
```

9.3.3 genVmapAsm

This utility is very useful when you wish to map sparse virtual memory to a compact physical memory. The utility is invoked as

```
genVmapAsm v_to_p_mapping.txt setup_page_tables.s
```

where v_to_p_mapping.txt contains virtual to physical page mappings and setup_page_tables.s is the assembly file which generates the page tables in memory for use during execution of the program.

Each line of the mapping file has the form

```
context-id virtual-addr phy-addr page-level [cacheable acc]
```

The cacheable and acc have default values 1 and 3 respectively. The acc value is to be specified as per the MMU specification in the Sparc-V8 ISA manual.

An example of a v_to_p_mapping.txt file is

```
0x0 0x0 0x0 0x1
0x0 0x40000000 0x80000 0x2
0x0 0xfffff000 0xff000 0x3 1 3
```

which specifies the following mappings (all for context 0): a level-1 page (16MB) from virtual address 0x0 to physical address 0x0, a level-2 page (256kB) from virtual address 0x40000000 to physical address 0x80000, and level-3 page (4kB) from virtual address 0xfffff000 to physical address 0xff000 (with cacheable=1, and acc=3).

9.3.4 The init.s file

The `setup_page_tables.s` file needs to be included as part of the initialization setup in order to set up the page tables before the actual program starts executing. A sample initialization file which does this is shown below

```
.global _start;
_start:
    set -256, %sp
    clr %fp

    ! note: wim is setup assuming that
    ! we start from window 7 (below). Window 0
    ! is marked invalid..
    !
    ! you will need to supply overflow/underflow
    ! trap handlers.
    set 0x1, %l0
    wr %l0, 0x0, %wim

    ! trap table.
    set trap_table_base, %l0
    wr %l0, 0x0, %tbr

    ! set up virtual -> physical map.
    ! (the page_table_setup code is
    ! in setup_page_tables.s)
    call page_table_setup
    nop

    ! update the context-table-pointer.
    ! (the set_context_table_pointer code
    ! is in setup_page_tables.s)
    call set_context_table_pointer
    nop

    ! enable traps.
    set 0x10E7, %l0
    wr %l0, %psr

    ! enable mmu.
    set 0x1, %o0
    sta %o0, [%g0] 0x4

    ! the main program.. GO
    call main
    nop
```

Chapter 10

Preparing a FLASH image for booting an application

We describe the procedure to be used in order to prepare a FLASH image for booting an application.

We assume that

- FLASH memory is mapped to physical address range 0x0 to 0x3ffffff
- SRAM is mapped to physical address range 0x40000000 to 0xffeffff
- Physical devices are mapped to address range 0xffff0000 to 0xffffffff

Typically, we will be given an application, which is to be loaded into SRAM by executing a program which resides on FLASH memory.

10.1 Compiling the application

We first compile and link the application you want to boot. The overall flow is illustrated in Figure 9.1.

For the assumptions shown above, we instruct the linker to place the text section at address 0x40000000, and the data section at 0x80000000. This can be done using the linker script shown below:

```
ENTRY(_start)
__DYNAMIC = 0;
SECTIONS
{
. = 0x40000000;
.text ALIGN(8) : {
KEEP(*( .text .ajitstart))
*(.text)
*(.text.*)
```

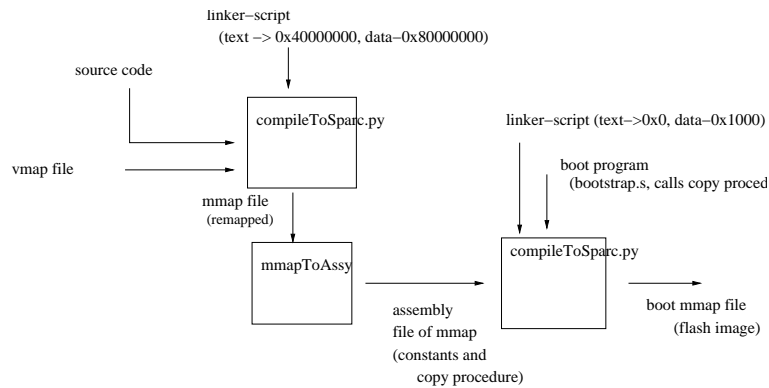


Figure 10.1: Preparing a boot flash image

```

KEEP(*(.text.pagetablesetup))
KEEP(*(.text.traphandlers))
KEEP(*(.text.traptablebase))
}
. = 0x80000000;
.rodata ALIGN(8) : { *(.rodata) *(.rodata.*) }
.data ALIGN(8) : { *(.data) *(.data.*) *(.bss) }
}

```

We may further use a vmap file for the compilation.

```

! I cacheable.
0x0 0x40000000 0x40000000 0x2 0x1 0x3
! D cacheable.
0x0 0x80000000 0x40020000 0x2 0x1 0x3
! Stack cacheable..
0x0 0xfffffe00 0x400fe000 0x3 0x1 0x3
! I/O non-cacheable
0x0 0xffff0000 0xffff0000 0x3 0x0 0x3

```

This uses 20 bits of physical memory address space to map the virtual address from 0x40000000 upwards.

The compilation produces an .mmap.remapped file.

10.2 Prepare the boot image

The mmapToAssyU64 utility is used to convert the application's .mmap.remapped file to an assembly program.

```
mmapToAssyU64 rpn.mmap.remapped assy.s 0x40000000 0x20000
```

This produces an assembly program which writes the application code image starting from address 0x40000000 into a data block of size 0x20000 (Note: this means that the application code image size must be at most 0x20000 bytes. In case of overflow, the routine will complain).

The `assy.s` file which is produced is then linked with a bootstrap `bootstrap.s` file (in directory `tools/flash_image/asm`). The `bootstrap.s` file contains the following:

```
.section .text.ajitstart
.global _start;
_start:
set -256, %sp
clr %fp

set 0x1, %l0 ! window 0 is marked invalid... we start at window 7
wr %l0, 0x0, %wim !

! enable traps.
set 0x10E7, %l0
wr %l0, %psr

! copy to sram..
call copy_program_image
nop

! jump to code.
call jump_to_code
nop

ta 0

!
! This is a small subroutine which copies
! memory bytes from one region to another.
!
! g3 contains starting source address, g4 contains
! number of bytes (must be > 0) to be copied,
! g5 contains the starting destination address.
!
.global _copy_segment;
_copy_segment:
    ldub [%g3], %l3
    stub %l3, [%g5]
    add %g3, 1, %g3
    add %g5, 1, %g5
    subcc %g4, 1, %g4
```

```
    bnz _copy_segment
    nop
    retl
    nop
```

After linking the `assy.s` and `bootstrap.s` files, using a linker script that maps text to location `0x0`, we get a bootstrap mmap file (lets say it is `bootstrap.mmap`). This needs to be written into the flash memory. In order to prepare a bin file of the mmap, use

```
mmapToBin 20 bootstrap.mmap bootstrap.bin
```

The `bootstrap.bin` file is copied to FLASH (`0x0` to `0x..`) and can be booted from address `0x0`.

Chapter 11

The AJIT FPGA based prototyping platforms

We have two FPGA based prototyping platforms currently available for evaluating the AJIT processor and for developing software for it.

- A KC705 based single board computer with flash memory and DRAM, which can be used to boot Linux and for programs which need large amounts of memory.
- A VC709 based bare platform with 4MB of SRAM and a large amount of resources available for building SOC prototypes.

11.1 KC705 board-based FPGA prototype of AJIT Single-board-computer

The KC705 based AJIT FPGA prototyping platform allows the use of the AJIT core in a single board computer setup with

- 16MB of FLASH memory.
- 128MB of DRAM.
- Serial UART for debug.
- Serial UART as a terminal driver.
- Integrated interrupt controller and timer.

The Linux 3.16.1 kernel can be booted on this platform. The internal structure of the platform on the KC705 board from Xilinx is shown in Figure 10.1.

Some points to note about this platform are

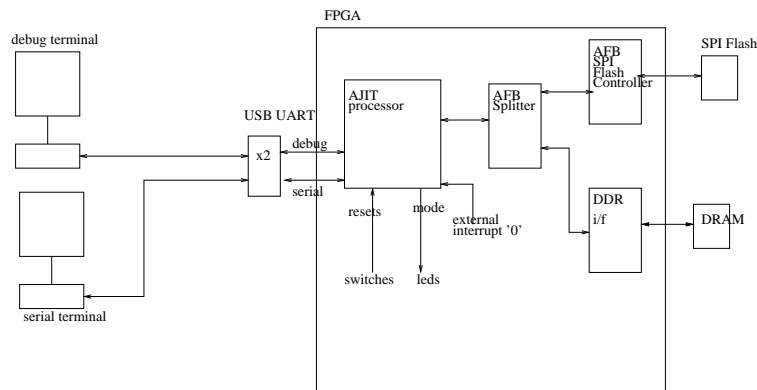


Figure 11.1: A standalone AJIT prototype platform

- The 64-bit bus (The AJIT core bus) from the processor core is split into two busses, one for controlling a flash memory device (16MB) and the other for connecting to the Xilinx DRAM controller (configured to control 128MB of DRAM).
- Two serial UARTs are provided: one for the debug connection, and one for a terminal.

The AFB splitter, and AFB SPI Flash Interface are building blocks that are included in the generic AJIT core distribution (see Chapter 7). The AFB splitter is used to divide the address space into a low space (for Flash, 0x0 to 0x3ffffff) and a high space (for DRAM, 0x40000000 to 0xffffffff). The AFB SPI Flash interface is used to control the SPI Flash memory device.

11.1.1 Using the KC705 platform

As indicated in Figure 10.1, the setup has the following:

- a debug terminal, which can be used to control and observe the prototype system using the `ajit.debug.monitor_mt` (ADM) utility. More details about the use of the ADM are provided in Chapter 8.
- a serial terminal: To provide terminal I/O to programs running on the prototype platform.
- The prototype FPGA card, which needs to be programmed with a bit-file which implements the processor and the peripherals inside the FPGA.

One can use the prototype in two ways:

- Load the program into high memory, and run it directly from there.
- Create a boot image to flash, and boot the image from flash.

These two options are described in more detail in Chapter 8.

11.1.2 Writing programs for the KC705 platform

From a software perspective, the platform consists of the processor core, peripherals and main memory. The memory map of the system is

```
FLASH
    0x0 to 0xffffffff
DRAM
    0x40000000 to 0x407ffffff

Interrupt-controller
    0xffff3000 to 0xffff301c

Timer (count-down)
    0xffff3100 to 0xffff311c

Serial device
    0xffff3204 to 0xffff3210

Scratch pad
    0xffff2c00 to 0xffff2ffc
```

A typical program would first enable the peripherals of interest and then jump to a main program. Details about using the peripherals are described in Chapter 7. Examples of test programs are given in the AJIT tool-chain repository (with and without the CORTOS2 environment).

We recommend that you use the CORTOS2 environment, which provides a simple abstract view of the platform.

11.2 VC709 board-based FPGA prototype of AJIT Single-board-computer

The VC709 based AJIT FPGA prototyping platform allows the use of the AJIT core in a bare system on chip setup with:

- 4MB of SRAM (single cycle block RAM on the FPGA).
- Serial UART for debug.
- Serial UART as a terminal driver.
- Integrated interrupt controller and timer.

The internal structure of the system on the VC709 board from Xilinx is shown in Figure 10.2.

Some points to note about this platform are

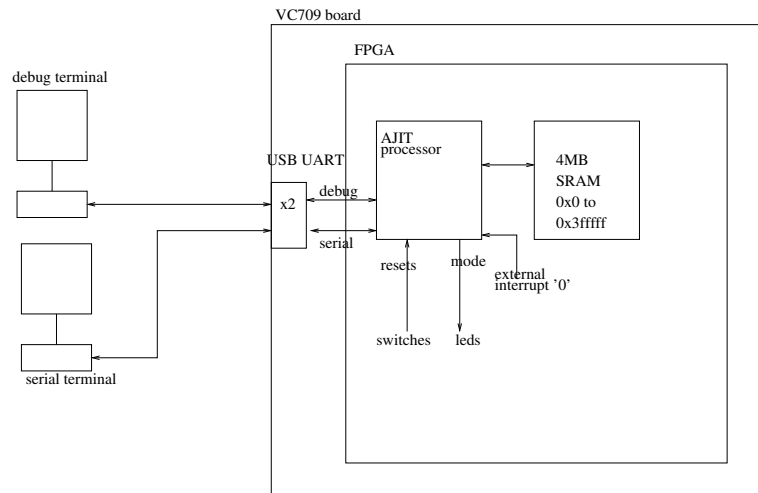


Figure 11.2: A standalone AJIT prototype platform on the VC709 card

- The 64-bit bus from the processor core is connected to a 4MB SRAM implemented using FPGA block RAM.
- Two serial UARTs are provided: one for the debug connection, and one for a terminal.

11.2.1 Writing programs for the VC709 platform

From a software perspective, the platform consists of the processor core, peripherals and main memory. The memory map of the system is

```

SRAM
    0x0 to 0x3fffff

Interrupt-controller
    0xffff3000 to 0xffff301c

Timer (count-down)
    0xffff3100 to 0xffff311c

Serial device
    0xffff3204 to 0xffff3210

Scratch pad
    0xffff2c00 to 0xffff2ffc
  
```

A typical program would first enable the peripherals of interest and then jump to a main program. Details about using the peripherals are described in Chapter 7. Examples of test programs are given in the AJIT tool-chain repository (with and without the CORTOS2 environment).

We recommend that you use the CORTOS2 environment, which provides a simple abstract view of the platform.

11.2.2 Setup for using the VC709 platform

As indicated in Figure 10.2, the setup to use the platform consists of the following components:

- a debug terminal, which can be used to control and observe the prototype system using the `ajit_debug_monitor_mt` (ADM) utility. More details about the use of the ADM are provided in Chapter 8.
- a serial terminal: To provide terminal I/O to programs running on the prototype platform.
- The prototype FPGA card, which needs to be programmed with a bit-file which implements the processor and the peripherals inside the FPGA.

One case use the prototype to run a program by first loading the program into memory starting from address 0x0, and then running the program on the processor. This options is described in more detail in Chapter 8.

Chapter 12

The debug infrastructure for AJIT processors

The AJIT CPU includes a debug support unit (DSU) which allows full controllability and observability of the CPU state. Using the DSU, the developer can

- Observe all registers and memory locations.
- Control all registers and memory locations.
- Set hardware break points.
- Set hardware watch points.

The AJIT debug monitor (described earlier in Section 8.1) can be used to connect to the DSU, and serve as the shell for a debugging session.

12.1 On chip debug scheme

Let us take the example of the 2x2 processor configuration. Within this processor, we have two cores, each of which has two threads. Thus there are four threads, which can be identified by a pair of numbers core-id, thread-id.

Each thread has a debug support unit interface which consists of command and response pipes. The processor has a debug multiplexor which manages the connection with each of the CPU's in the processor. The multiplexed debug connection connects to a host computer using USB-UART device.

On the host side, a debug server with one thread per AJIT CPU being debugged is started. At the same time, client debug sessions (one for each AJIT CPU) are started. Once the client connects to the server, the control of that CPU is managed by the GDB remote client in the usual way.

This setup is shown in Figure 11.1.

Using this debug setup:

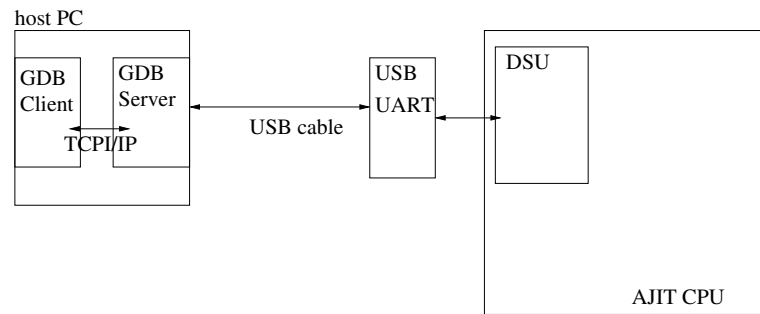


Figure 12.1: AJIT Multi-CPU debug setup

- It is possible to concurrently debug all the AJIT CPU threads that are active inside the processor.

Bibliography

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