TSEA44: Computer hardware – a system on a chip

Lecture 3: The OR1200 Soft CPU

LINKÖPING UNIVERSITY

Agenda

- OR1200
  - Architecture
  - Instruction set
  - C example
- Wishbone bus
  - Cycles
  - Arbitration
  - SV interface
  - Lab 1
- OR12
  - Pipelining etc.

Practical Issues

- Lab1 – Lab4 solved in groups of 1-3 student each
  - Not allowed to form group unless all students in the group have a pass on Lab 0
  - List of students with pass on lab0 shown in lisam course room
    - Easier to know who is looking for group members
    - Text file Results_2022.txt located in the Course Documents tab

Practical Issues, cont.

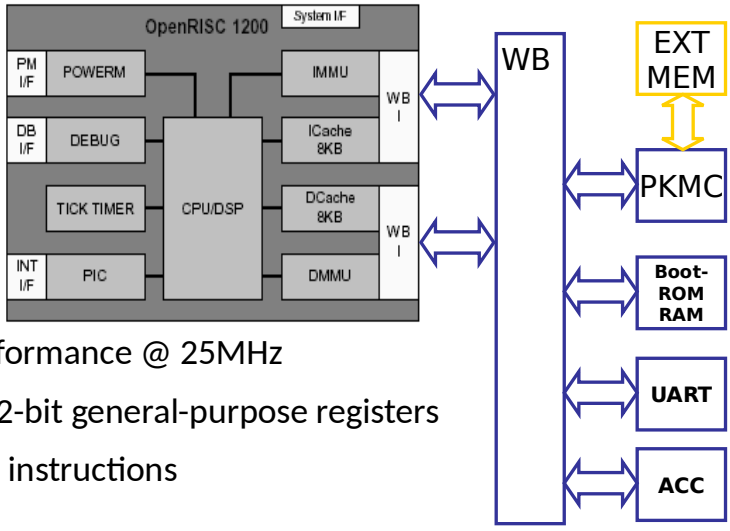
- Once labgroups defined, a shared location will be available
  - /courses/TSEA44/labs/labgrpXX
- To allow everyone in the group access, setup your umask when working in labgrpXX folder
  - umask 7
  - NOTE: Only do this when working in the shared directory
    - Will make all newly created files in e.g. your home folder readable to everyone!

Some soft CPUs

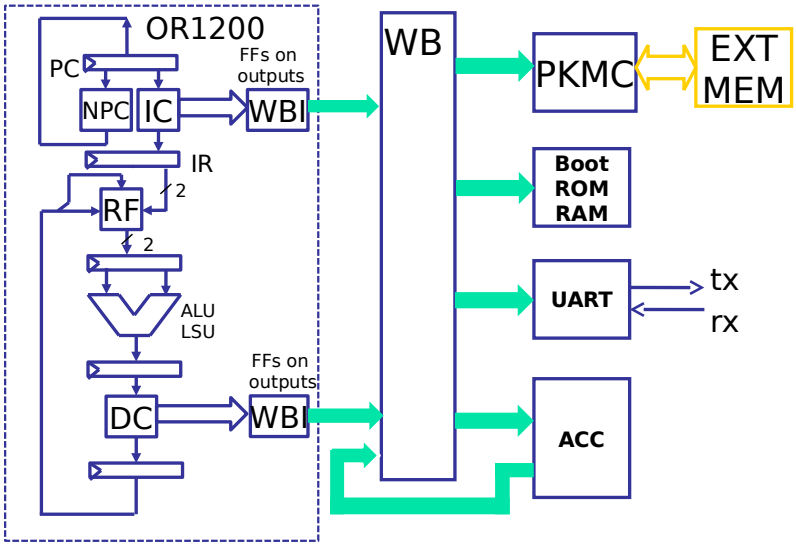
	Open RISC	Leon	Nios	Micro-Blaze	RISCV
who	opencores	gaisler	altera	Xilinx	riscv.org
what	verilog	VHDL	netlist	netlist	various
CPU stages	RISC 5	RISC 5	RISC 6/5/1	RISC 3	RISC
cache	Direct IC/DC	IC/DC	IC/DC	IC/DC	IC/DC
MMU	Split IMMU DMMU				IMMU/ DMMU
bus	Wishbone simple/Xbar	AMBA (AHP/APB)	Avalon	LMB/OPB/ FSL	amba/ AXI

OpenRISC 1200 RISC Core

- 5 stage pipeline
- Single-cycle execution on most instructions
- 25 MIPS performance @ 25MHz
- Thirty-two 32-bit general-purpose registers
- Custom user instructions



Traditional RISC pipeline

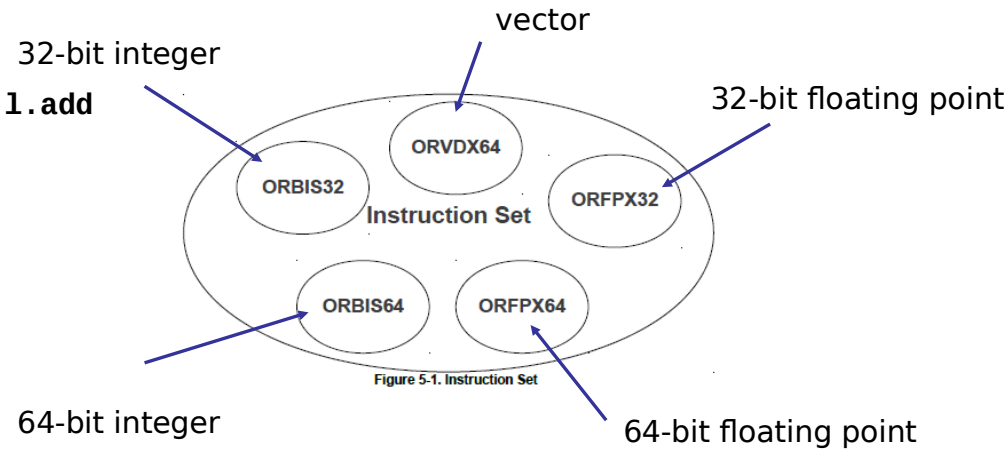


Instruction Set Architecture

- IC and DC compete for the WB
  - Reduce usage of data memory
    - Many register
    - All arithmetic instructions only access registers
    - Only load/store access to memory
  - Reduce usage of stack
    - Save return address in link register **r9**
    - Parameters to functions in registers

Instruction set

- Divided into classes:



Instruction descriptions

l.add *Add*

31 26	25 . . . 21	20 . . . 16	15 . . . 11	10	9 8	7 . . 4	3 . . 0
opcode 0x38	D	A	B	reserved	opcode 0x0	reserved	opcode 0x0
6 bits	5 bits	5 bits	5 bits	1 bits	2 bits	4 bits	4bits

```
l.add rD,rA,rB      ; rD = rA + rB
                    ; SR[CY] = carry
                    ; SR[OV] = overflow
```

l.lw *Load Word*

31 26	25 . . . 21	20 . . . 16	15 0
opcode 0x21	D	A	I
6 bits	5 bits	5 bits	16bits

```
l.lw rD,I(rA)      ; rD = M(exts(I) + rA)
```

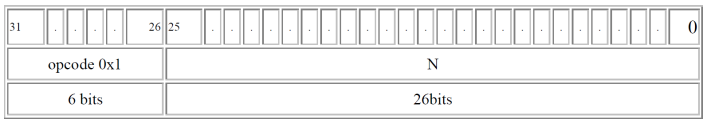
Example of code

```
l.movhi r3,0x1234    // r3 = 0x1234_0000

l.ori   r3,r3,0x5678 // r3 |=  0x0000_5678

l.lw    r5,0x5(r3)   // r5 = M(0x1234_567d)

l.sfeq  r5,r0        // set conditional branch
                     // flag SR[F] if r5==0

l.bf    somewhere    // jump if SR[F]==1

l.nop                // 1 delay slot, always executed
```

(1 additional HW NOP inserted if jump taken)

Subroutine jump instruction

`l.jal` Jump and Link



Format:
`l.jal N`

Example instruction sequence:

```
JIA:    l.jal N
DIA:    l.xxx
DIA+4:  l.yyy
```

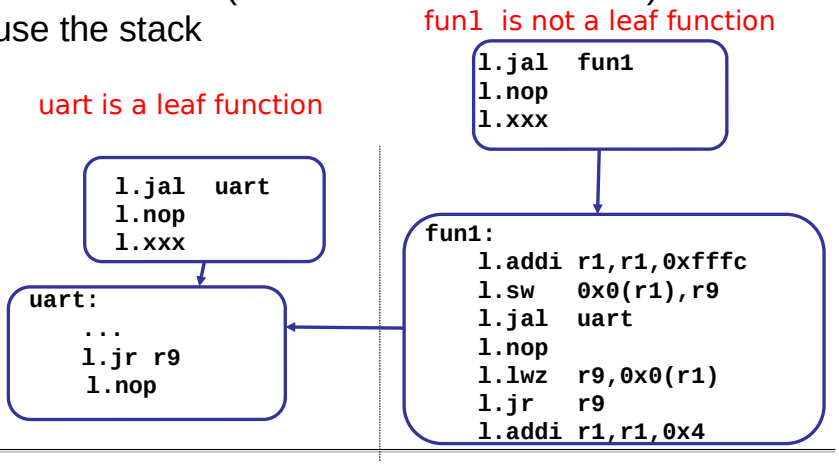
Description:
The immediate value is shifted left two bits, sign-extended to program counter width, and then added to the address of the jump instruction. The result is the effective address of the jump. The program unconditionally jumps to EA with a delay of one instruction. **The address of the instruction after the delay slot is placed in the link register**.

32-bit Implementation:

```
PC = exts(Immediate < < 2) + JumpInsnAddr = 4N + JIA
LR = DelayInsnAddr + 4                    = DIA+ 4
```

Subroutine jump use

- In this implementation LR (link register) is r9
- A leaf function (no further subroutine calls) does not use the stack



Register usage

- ABI = Application Binary Interface

R11	RV function return value
R9	LR (link register)
R3-R8	Function parameters 0-5
R2	FP (frame pointer)
R1	SP (stack pointer)
R0	=0

A very simple C example

```
int sum(int a, int b)
{

  return(a+b);
}


int main(void)
{
  int a=1,b=2, nr;

  nr = sum(a,b);

  return(nr);
}
```

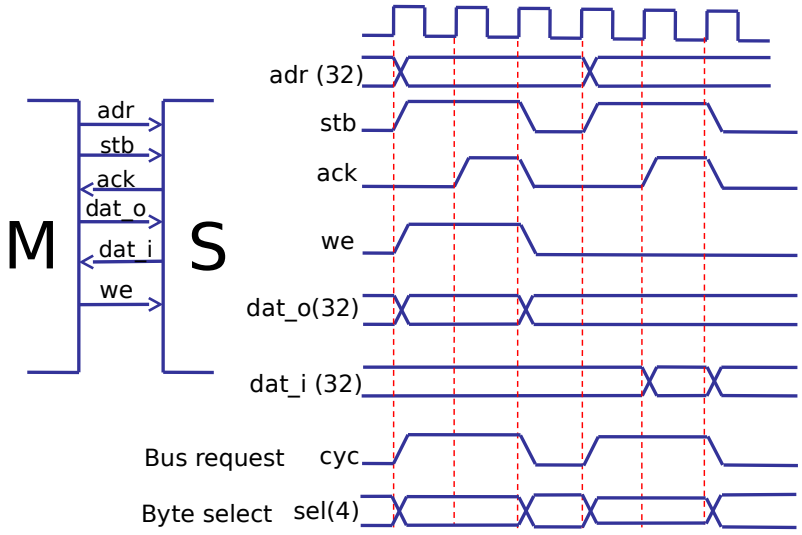
```
l.add r3,r3,r4          ; a = a+b
l.ori r11,r3,0x0        ; rv = a
l.jr r9                 ; return
l.nop
```

```
l.addi r1,r1,0xfffffffc   ; sp -= 4
l.sw 0x0(r1),r9           ; M(sp)= lr

l.addi r3,r0,0x1          ; a = 1
l.jal  _sum
l.addi r4,r0,0x2          ; b = 2

l.lwz r9,0x0(r1)          ; lr = M(sp)

l.jr r9                   ; return
l.addi r1,r1,0x4          ; sp += 4
```

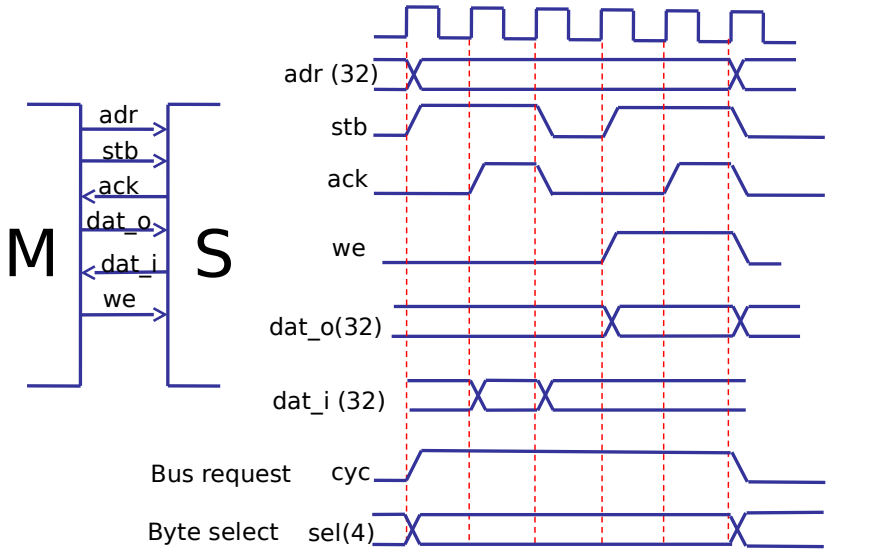

The Wishbone Interconnect

- Some features
  - Intended as a standard for connection of IP cores
  - Full set of popular data transfer bus protocols including:
    - READ/WRITE cycle
    - RMW cycle
    - Burst cyles
  - Variable core interconnection methods support point-to-point, shared bus, and crossbar switch
  - Arbitration method is defined by the end user (priority arbiter, **round-robin arbiter**, etc.)

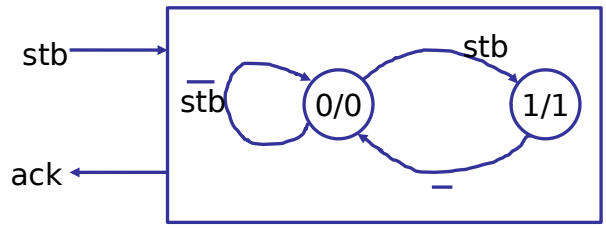
Simple Wishbone cycles

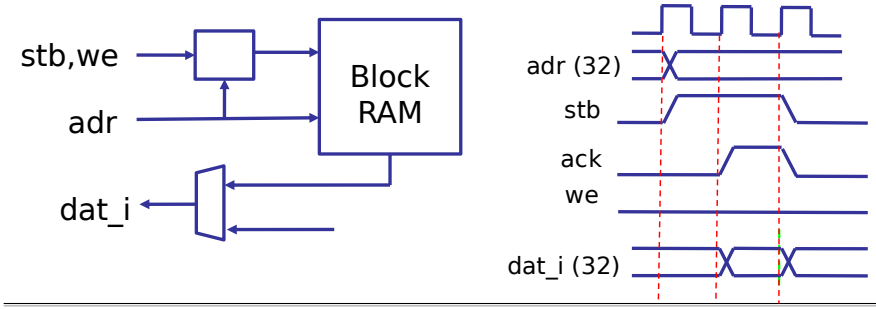


Read-modify-write cycle

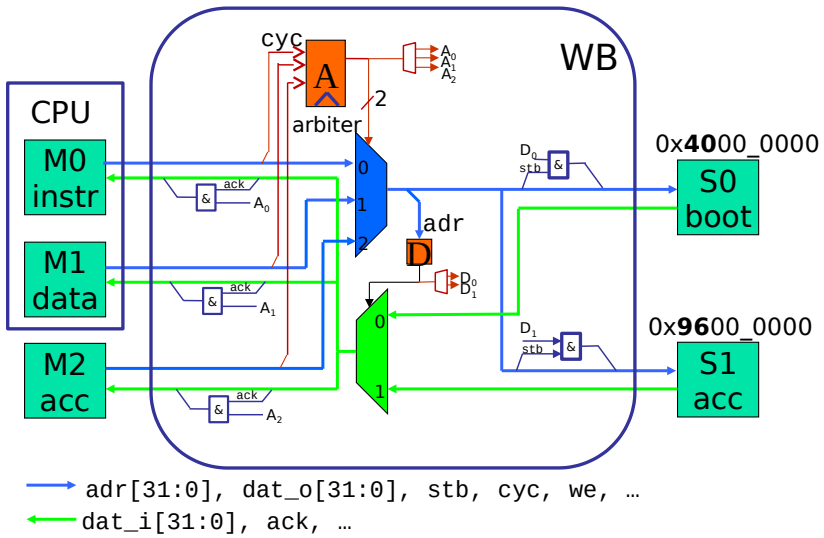


Ack FSM in each slave





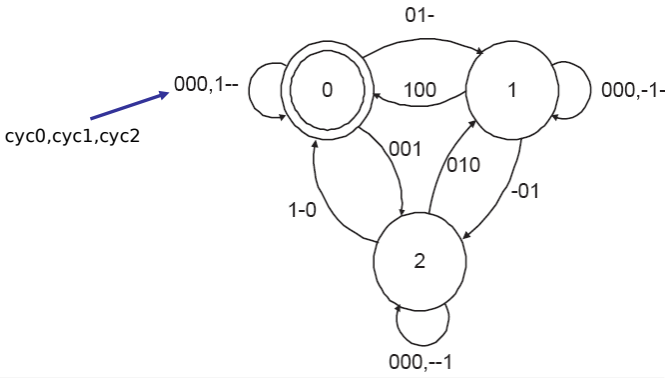
Wishbone bus (3M, 2S)



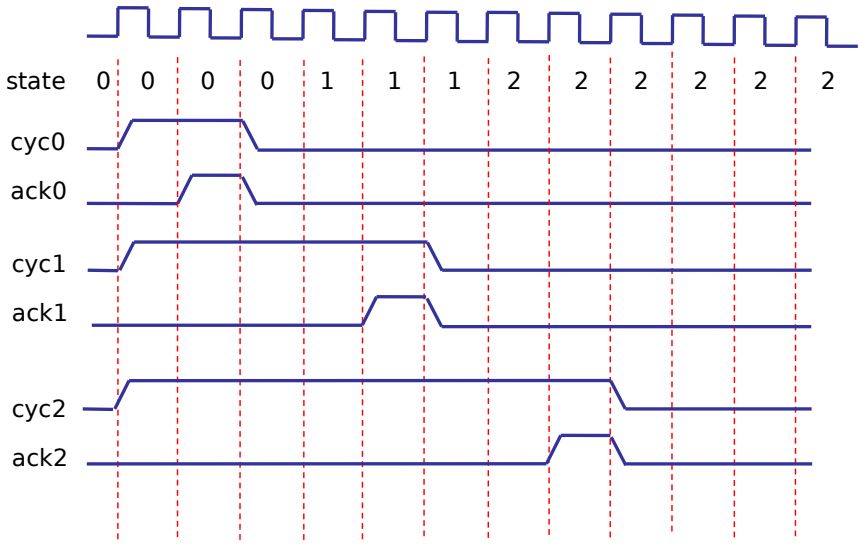
Round robin arbiter

state	priority
0	0,1,2
1	1,2,0
2	2,0,1

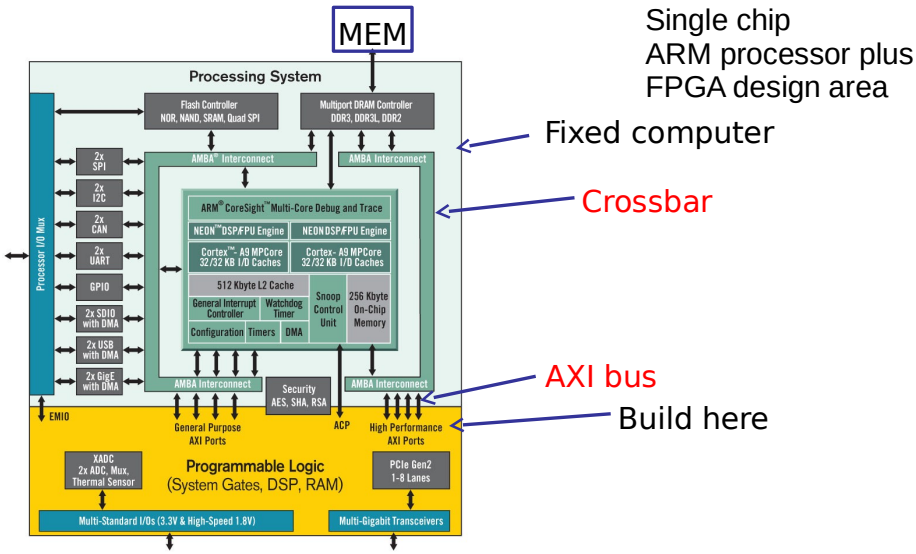
A master cannot be forced off the bus. Release the bus by deasserting cyc!



Wishbone cycles with arbitration



Comparison to Xilinix Zynq (in Zedboard)



Single chip
ARM processor plus
FPGA design area

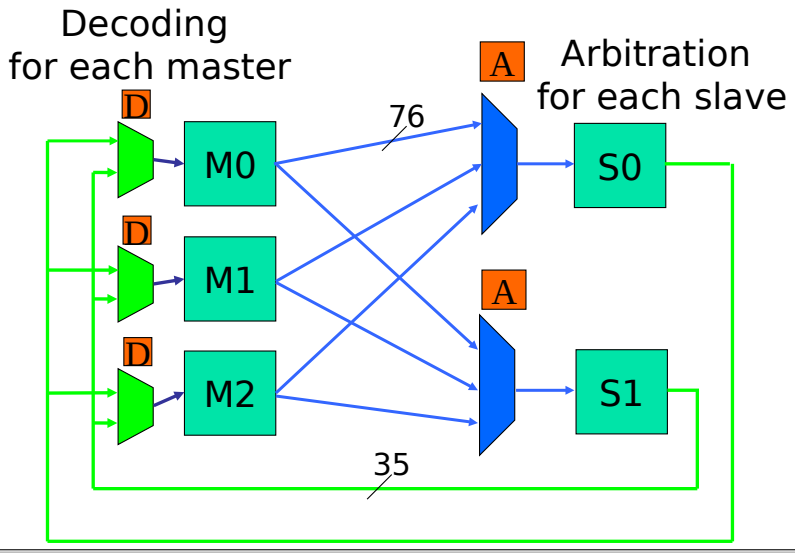
Fixed computer

Crossbar

AXI bus

Build here

Crossbar



AXI (ARM standard)

- Address/control phases are separate from data phases
- Burst possible with only start adress issued
- Read and write data channels are separate

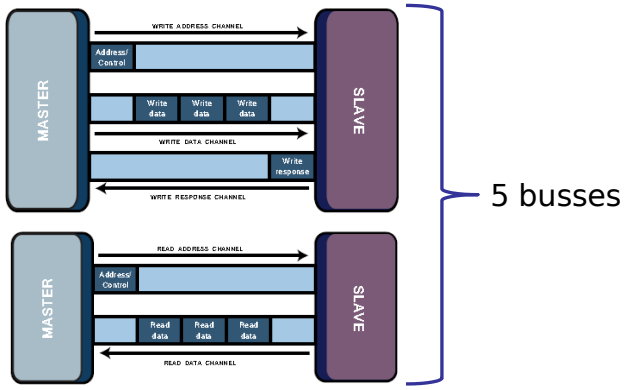
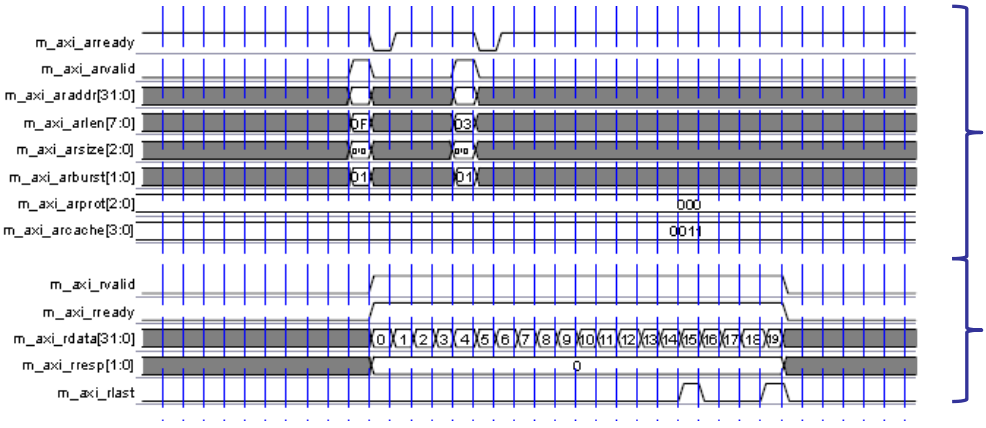


Figure 19.2: AXI4 read channel architecture

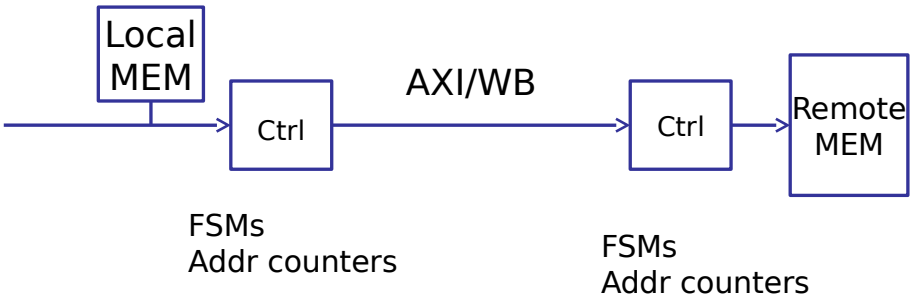
Example: AXI read burst

- 2 busses: Read adress bus, read data bus



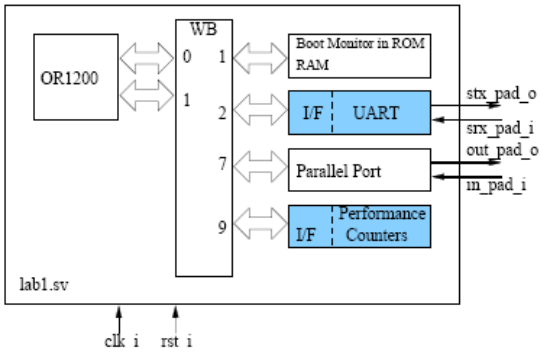
Burst mode comment:

- Require controller at both ends



Lab 1

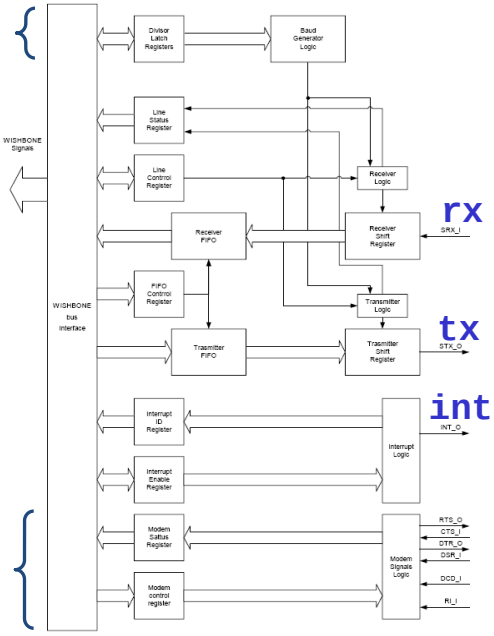
1. modify your UART from previous lab and interface it to the Wishbone bus
2. check the uart device drivers in the boot monitor. Your UART will replace an existing UART 16550.



3. download and execute a benchmark program, that performs (the DCT part of) JPEG compression on a small image in your RAM module
4. simulate the computer running the benchmark program
5. design a module containing hardware performance counters

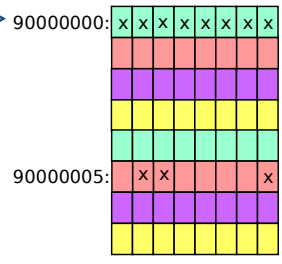
UART IP Core (16550)

- Compatible with industri standard 16550
- 16 character FIFOs for rx and tx
- Seven 8-bit registers on a 32-bit bus
- Full description in course material (UART specification)
- We do not use all registers in our board
  - Modem control lines
  - Baud rate dividor control



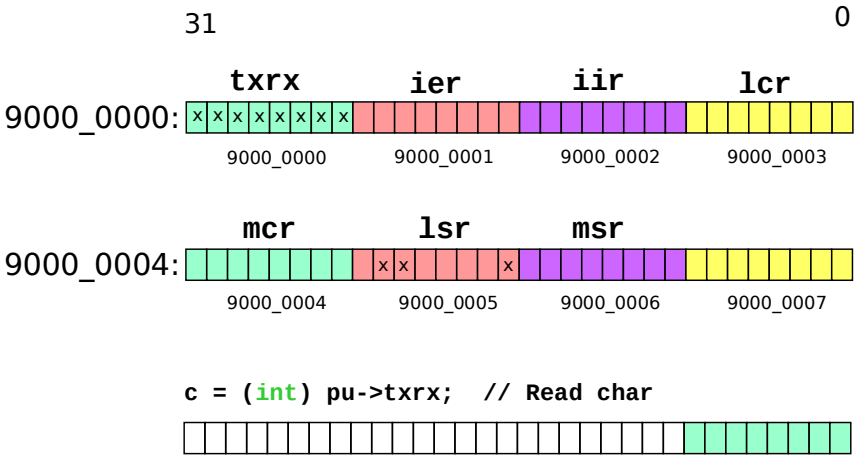
UART 16550-driver in the monitor

```
typedef struct
{
    unsigned char txrx;    // 0. transmit(W), receive(R)
    unsigned char ier;     // 1. interrupt enable (RW)
    unsigned char iir;     // 2. interrupt flags(R),FIFO ctrl(W)
    unsigned char lcr;     // 3. line control (RW)
    unsigned char mcr;     // 4. modem control (W)
    unsigned char lsr;     // 5. line status (R)
    unsigned char msr;     // 6. modem status (R)
} UART;

UART volatile *pu = (UART *) 0x90000000;
int c;

…

// It takes 2170 clocks to tx/rx a character
// with 25 MHz clock. Handshake needed!

while (!(pu->lsr & 0x01)) // has the character been received?
  c = (int) pu->txrx;     // read char

while (!(pu->lsr & 0x60))          // has the character been transmitted
  pu->txrx = (unsigned char) c;    // write new char
```



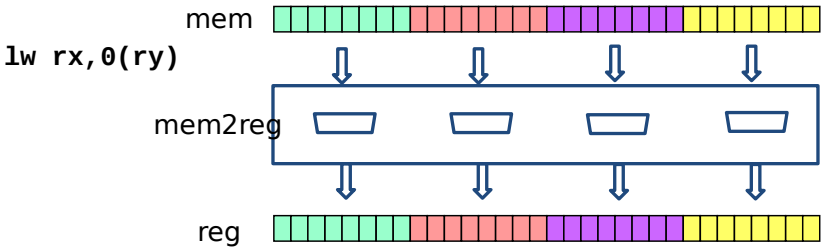
Or1200 is a 32-bit machine

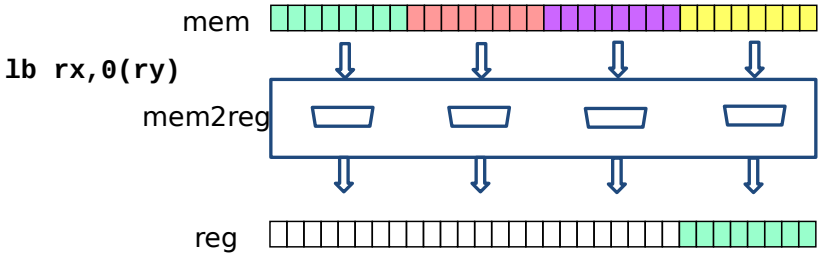
- The bytes are ordered like this (big-endian)



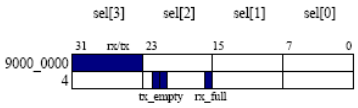

```
c = (int) pu->txrx;  // Read char
```


Bytes, halfwords can be read/written





Programmers model



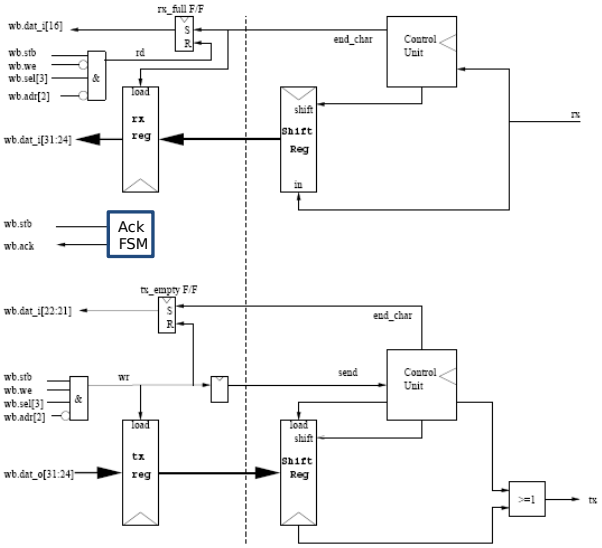
Existing driver wants this

Handshake F/Fs

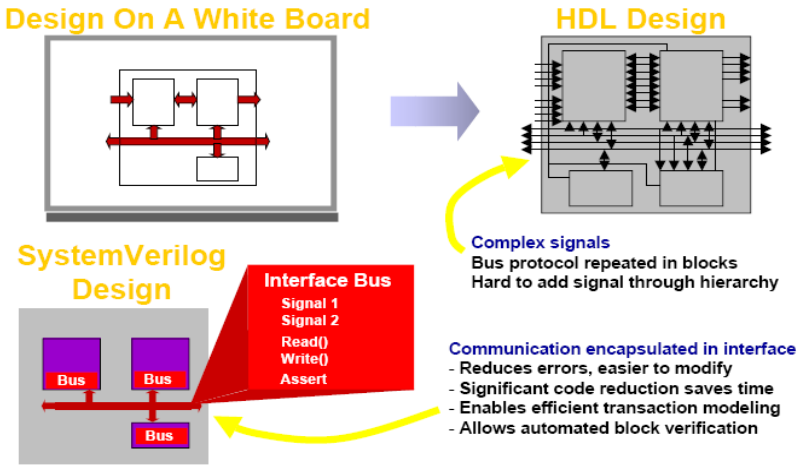
rx_full Set: end_char
Reset: read txrx

tx_empty Set: end_char
Reset: write txrx

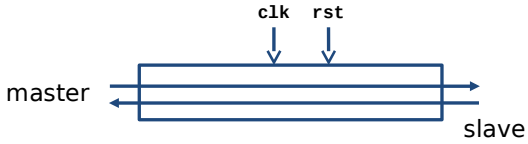
Block diagram



SystemVerilog – Interfaces
”a bundle of wires”



Interface definition

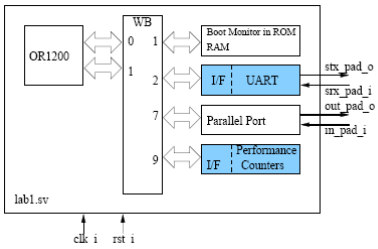



```
interface wishbone(input logic clk, rst);
   typedef logic [31:0] adr_t;
   typedef logic [31:0] dat_t;

   adr_t       adr; // address bus
   dat_t       dat_o;    // write data bus
   dat_t       dat_i;    // read data bus
   logic       stb; // strobe
   logic       cyc; // cycle valid
   logic       we;  // indicates write transfer
   logic [3:0] sel; // byte select
   logic       ack; // normal termination
   logic       err; // termination w/ error
   logic       rty; // termination w/ retry
   logic       cab; //
   logic [2:0] cti; // cycle type identifier
   logic [1:0] bte; // burst type extension


   modport master(
      output      adr, dat_o, stb, cyc, we,
                  sel, cab, cti, bte,
      input       clk, rst, dat_i, ack, err, rty);
```

```
   modport slave(
      input       clk, rst, adr, dat_o,
                  stb, cyc, we, sel, cab,
                  cti, bte,
      output      dat_i, ack, err, rty);

   modport monitor(
      input       clk, rst, adr, dat_o,
                  stb, cyc, we, sel, cab,
                  cti, bte,dat_i, ack,
                  err, rty);

endinterface: wishbone
```

LINKÖPING UNIVERSITY

Top file: lab1.sv

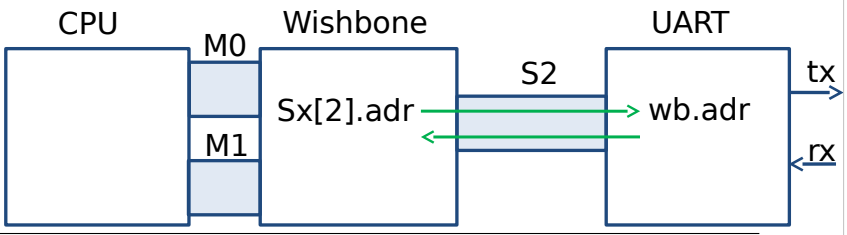



```
module lab1
  (input clk, rst,
   output tx,
   input  rx);

   wishbone m0(clk,rst), m1(clk,rst),
            s1(clk,rst), s2(clk,rst), s7(clk,rst), s9(clk,rst);

   or1200_top cpu(.m0(m0), .m1(m1), …);

   wb_top w0(.*);

   romram rom0(s1);

   lab1_uart my_uart(.wb(s2), .int_o(uart_int),
                     .stx_pad_o(tx),.srx_pad_i(rx));

   …

endmodule
```

LINKÖPING UNIVERSITY

In the wishbone end (wb/wb_top.sv)

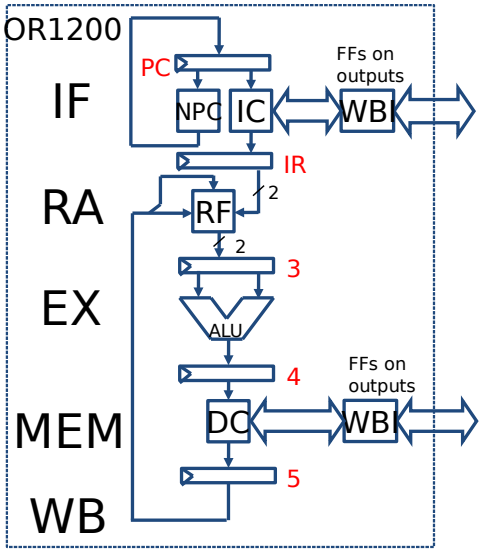
```
module wb_top(
  input clk_i, rst_i,

  // Connect to Masters
  wishbone.slave Mx[0:`Nm-1],

  // Connect to Slaves
  wishbone.master Sx[0:`Ns-1]
  );

// muxes!

endmodule
```



In the UART end: lab1/lab1_uart_top.sv

```
module lab1_uart_top(wishbone.slave wb,
                     output int_o,
                     input srx_pad_i,
                     output stx_pad_o);

   assign int_o = 1'b0;  // Interrupt, not used in this lab

   // Here you must instantiate lab0_uart
   // You will also have to change the interface of
   // lab0_uart to make this work.
   assign wb.dat_i = 32'h0;
   assign wb.ack = wb.stb;
   assign wb.err = 1'b0;
   assign wb.rty = 1'b0;


   assign stx_pad_o = srx_pad_i; // Change this line.. :)
endmodule
```

Pipelining and diagram




```
0: ld r1,0xb(r3)
4: add
8: sub
12: xxx
```

PC	IR	3	4	5
4	ld			
8	add	ld		
12	sub	add	ld	
16	xxx	sub	add	ld
20		xxx	sub	add

Lab 1 cont.: Performance counters

- Two master ports from CPU
  - M0: instruction fetch
  - M1: data in/out
- Measure time spent on waiting for instructions/data to/from memory
  - Cyc and Stb active
- Measure number of instruction/data words fetch/stored in memory
  - Ack active
- Remember printouts will introduce additional instructions and data transfers
  - Store counter values in local variables before calculating difference and printing

Pipelining

`l.add r3,r2,r1`

- fetch from IC (M)
- read r2,r1 from RF
- add
- write back r3 to RF

`l.lwz r3,0xb(r1)`

- fetch from IC
- read r1 from RF
- add r1 + 0xb
- read operand from DC (M)
- write back r3

`l.sw 0xb(r1),r3`

- fetch from IC
- read r1,r3 from RF
- add r1 + 0xb
- write operand to DC

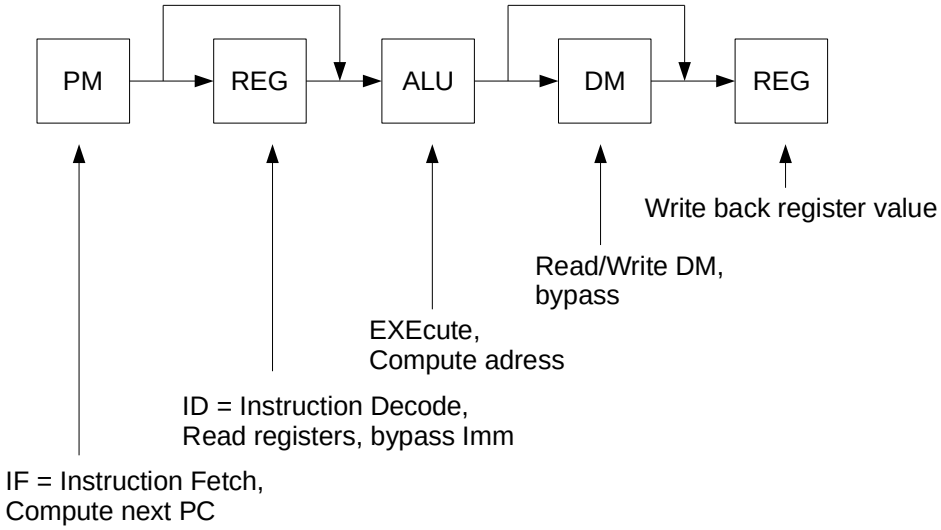
4-5 stages?

Classic RISC pipeline

	PM	RF	ALU	DM
PC	IR	3	4	5
4	ld			
8	add	ld		
12	sub	add	ld	
16	xxx	sub	add	ld
20		xxx	sub	add

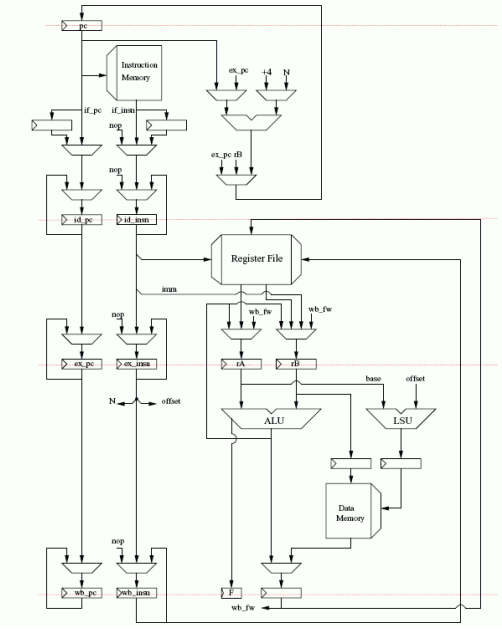
- Add,sub do nothing in the DM stage
- Instruction decode and read register simultaneously

The standard pipeline

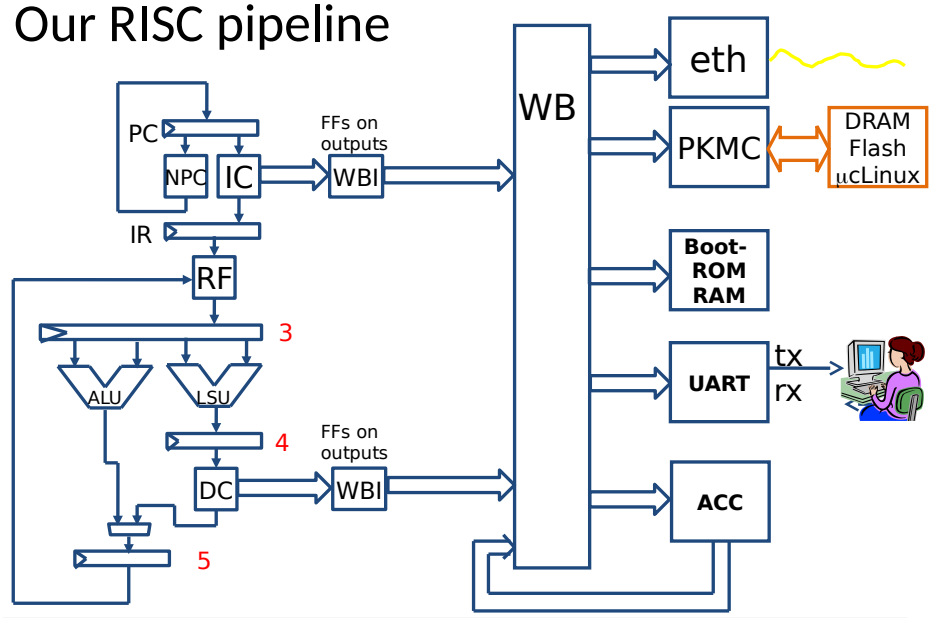


Our RISC pipeline

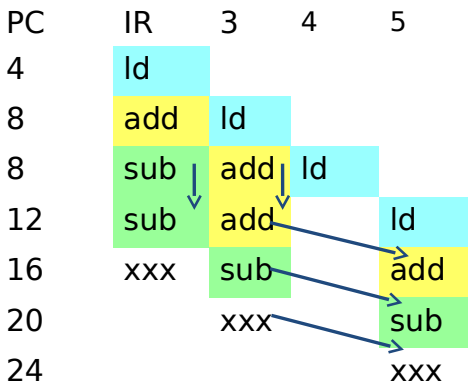
- IF = Instruction fetch, compute next PC
- ID - Instruction Decode, read registers
- EX – instruction execute, access DM
- WB – Write back register



Our RISC pipeline

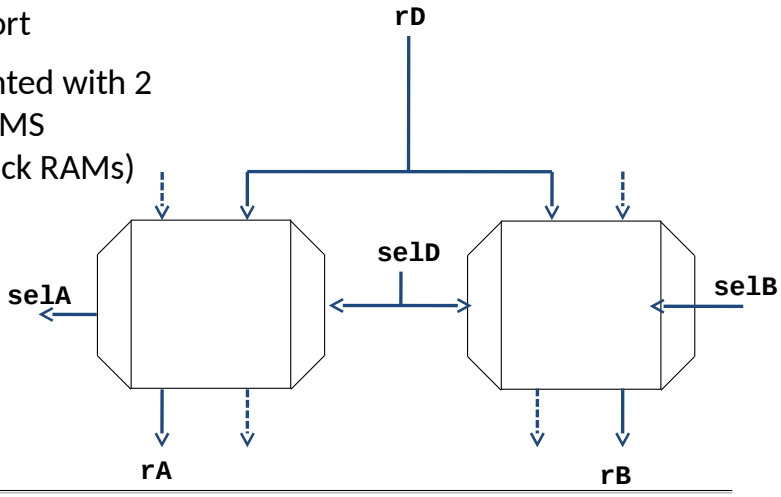


OR1200 pipeline



Register file

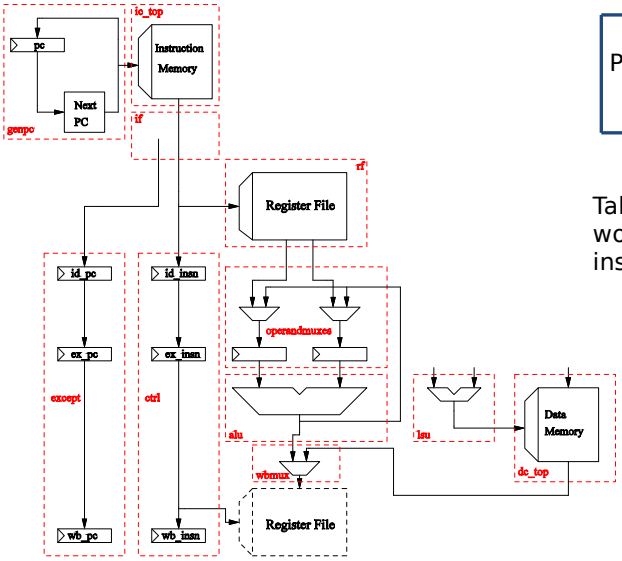
- 3-port RAM, 2 read ports and 1 write port
- Implemented with 2 2-port RAMS (Xilinx block RAMs)

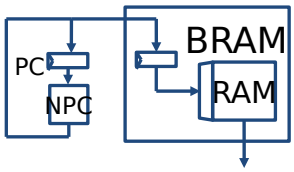


Block RAM 512x32 simulation model

```
// Generic single-port synchronous RAM model
module (input clk,we,ce,oe,
        input [8:0] addr,
        input [31:0] di,
        output [31:0] doq);

// Generic RAM's registers and wires
reg [31:0]  mem [0:511];        // RAM content
reg [31:0]  addr_reg;       // RAM address register

// RAM address register
always @(posedge clk)
  if (ce)
    addr_reg <= addr;

// Data output drivers
assign doq = (oe) ? mem[addr_reg] : 32'h0;

// RAM write
always @(posedge clk)
  if (ce && we)
    mem[addr] <= di;
```

Or1200 pipeline - schematic

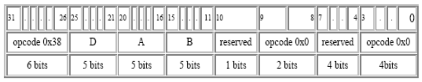




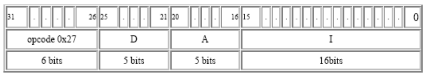
Take care when working with instantiated BRAMs

Lets study a few instructions

`l.add rD,rA,rB`



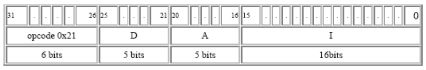
`l.addi rD, rA,K`



`l.sfeq rA,rB`

`l.bf N`

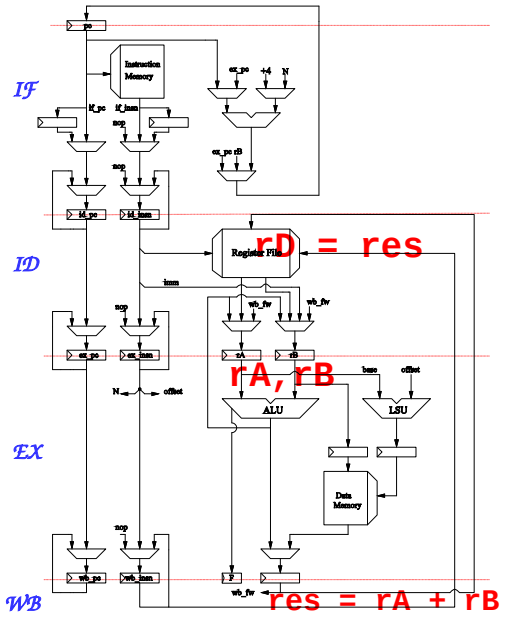
`l.lwz rD, I(rA)`



`l.sw I(rA),rB`

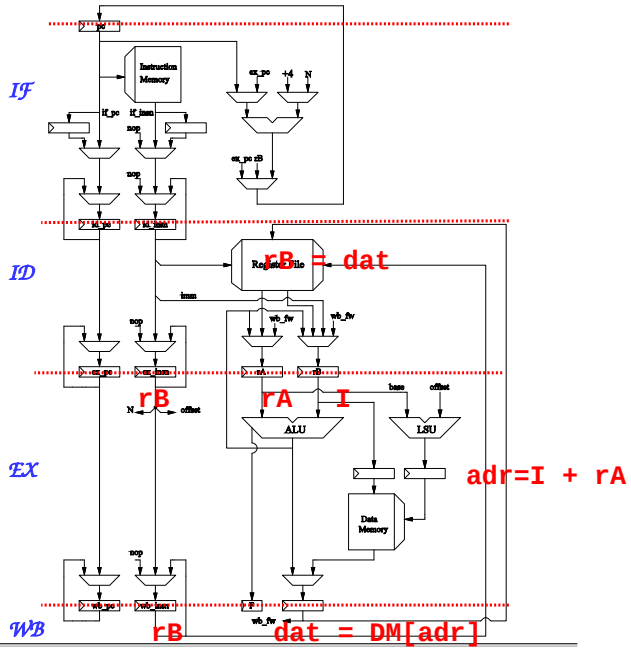
l.add rD, rA, rB

- rD stored in middle pipeline
- LSU not used
- 4 pipeline steps



lw rB, I(rA)

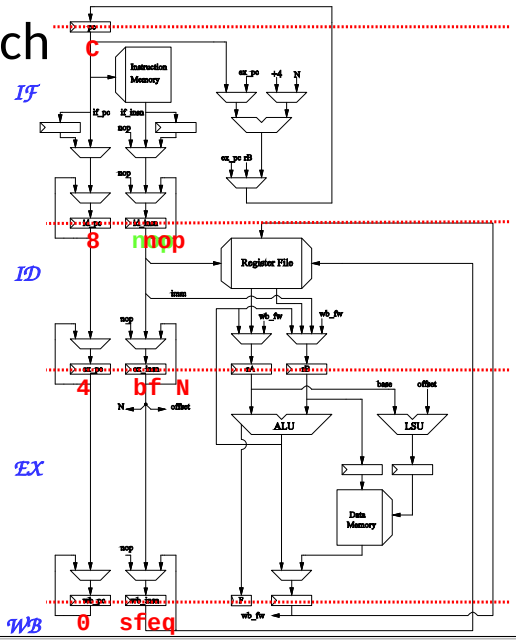
- Include extra pipeline stage in EX phase



Conditional branch

```
0:sfeq
4:bf N
8:nop
C:xxx
…
20:yyy
```

- 1 delay slot
- 1 extra HW nop on taken branch



www.liu.se

LINKÖPING UNIVERSITY