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Mestrado Integrado em Engenharia de Computadores e Telemática

Arquitectura de Computadores Avançada

DLX – Pipelining 1

Academic year 2020/2021 Adaptation of exercise guide by Nuno Lau/José Luís Azevedo

2. Consider the programs `ex_1.s` and `ex2.s` located in the directory `./DLX/apps/dlx_apps` in turn. Read them carefully, trying to understand what they do.

```

                                ; ex1.s
        .text
        .global  main
main:    addi     r2,r0,2        ; r2 = 2
        addi     r3,r0,3        ; r3 = 3
        addi     r5,r0,5        ; r5 = 5
        addi     r7,r0,7        ; r7 = 7
        addi     r9,r0,9        ; r9 = 9
        addi     r11,r0,11       ; r11 = 11
        add      r1,r2,r3
        sub      r4,r1,r5
        and      r6,r1,r7
        or       r8,r1,r9
        xor      r10,r1,r11
        trap     0              ; end of program

```

- 2.1. Determine the values that should be stored in the registers at the end of the execution.

$r1 = 5$ $r4 = 0$ $r6 = 5$
 $r8 = 13 = 0xD$ $r10 = 14 = 0xE$

- 2.2. Sketch the clock cycle diagram of the execution in a processor with the five-stage pipeline architecture depicted below.

Instruction	Clock cycle															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
addi \$2,\$0,2	IF	ID	EX	MEM	WB											
addi \$3,\$0,3		IF	ID	EX	MEM	WB										
addi \$5,\$0,5			IF	ID	EX	MEM	WB									
addi \$7,\$0,7				IF	ID	EX	MEM	WB								
addi \$9,\$0,9					IF	ID	EX	MEM	WB							
addi \$11,\$0,11						IF	ID	EX	MEM	WB						
add \$1,\$2,\$3							IF	ID	EX	MEM	WB					
sub \$4,\$1,\$5								IF	ID	EX	MEM	WB				
and \$6,\$1,\$7									IF	ID	EX	MEM	WB			
or \$8,\$1,\$9										IF	ID	EX	MEM	WB		
xor \$10,\$1,\$11											IF	ID	EX	MEM	WB	
trap 0												IF	ID	EX	MEM	WB

- 2.3. Run the code in the DLX simulator with the *forwarding* option turned off. Check if the execution is correct. If not, explain what has happened?

$r1 = 5$ $r4 = -5 = 0xFFFFFFFFB$ $r6 = 0$
 $r8 = 13 = 0xD$ $r10 = 14 = 0xE$

Register 1 is written in clock cycle 10 and read in clock cycles 8 and 9 (see diagram above).

- 2.4. Intersperse `nop` instructions in the code so that the program now behaves as expected. What is the new clock cycle count for running the program?

```
.text
.global  main
main:    addi    r2,r0,2      ; r2 = 2
         addi    r3,r0,3      ; r3 = 3
         addi    r5,r0,5      ; r5 = 5
         addi    r7,r0,7      ; r7 = 7
         addi    r9,r0,9      ; r9 = 9
         addi    r11,r0,11     ; r11 = 11
         add     r1,r2,r3
         nop
         nop
         sub     r4,r1,r5
         and     r6,r1,r7
         or      r8,r1,r9
         xor     r10,r1,r11
         trap    0            ; end of program
```

18 clock cycles.

- 2.5. Run the original code in the DLX simulator with the *forwarding* option turned on. Compare the results with the previous runs.

The program behaves as expected, the `NOP` instructions are not required.

2. Consider the programs `ex_1.s` and `ex2.s` located in the directory `./DLX/apps/dlx_apps` in turn. Read them carefully, trying to understand what they do.

```

                                ; ex2.s
        .text
        .global  main
main:    addi     r2,r0,0x4000    ; r2 = 0x4000
        addi     r5,r0,5        ; r5 = 5
        addi     r7,r0,7        ; r7 = 7
        addi     r9,r0,9        ; r9 = 9
        lw       r1,0(r2)
        sub      r4,r1,r5
        and      r6,r1,r7
        or       r8,r1,r9
        trap     0              ; end of program

```

- 2.1. Determine the values that should be stored in the registers at the end of the execution.

```

r1 = 0x20024000      r4 = 0x20023FFB
r6 = 0               r8 = 0x20024009

```

- 2.2. Sketch the clock cycle diagram of the execution in a processor with the five-stage pipeline architecture discussed at the lectures.

Instruction	Clock cycle												
	0	1	2	3	4	5	6	7	8	9	10	11	12
addi r2,r0,0x4000	IF	ID	EX	MEM	WB								
addi r5,r0,5		IF	ID	EX	MEM	WB							
addi r7,r0,7			IF	ID	EX	MEM	WB						
addi r9,r0,9				IF	ID	EX	MEM	WB					
lw r1,0(r2)					IF	ID	EX	MEM	WB				
sub r4,r1,r5						IF	ID	EX	MEM	WB			
and r6,r1,r7							IF	ID	EX	MEM	WB		
or r8,r1,r9								IF	ID	EX	MEM	WB	
trap 0									IF	ID	EX	MEM	WB

- 2.3. Run the code in the DLX simulator with the *forwarding* option turned off. Check if the execution is correct. If not, explain what has happened?

```

r1 = 0x20024000      r4 = 0xFFFFFFFFB
r6 = 0               r8 = 0x20024009

```

`r1` is written in clock cycle 8 and read in clock cycles 6 and 7 (see diagram above).

- 2.4. Intersperse `nop` instructions in the code so that the program now behaves as expected. What is the new clock cycle count for running the program?

```

        .text
        .globl  main
main:    addi     r2,r0,0x4000    ; r2 = 0x4000
        addi     r5,r0,5        ; r5 = 5
        addi     r7,r0,7        ; r7 = 7
        addi     r9,r0,9        ; r9 = 9
        lw       r1,0(r2)
        nop
        nop
        sub      $4,$1,$5
        and      $6,$1,$7
        or       $8,$1,$9
        trap     0              ; end of program

```

15 clock cycles.

- 2.5. Run the original code in the DLX simulator with the *forwarding* option turned on. Compare the results with the previous runs.

The program behaves as expected, but one NOP instruction is always required.

```
.text
.globl    main
main:     addi    r2,r0,0x4000    ; r2 = 0x4000
          addi    r5,r0,5        ; r5 = 5
          addi    r7,r0,7        ; r7 = 7
          addi    r9,r0,9        ; r9 = 9
          lw      r1,0(r2)
          nop
          sub     $4,$1,$5
          and     $6,$1,$7
          or      $8,$1,$9
          trap    0              ; end of program
```

3. Write a program that adds up the values of an integer array stored in memory. Run the code in the DLX simulator with the *forwarding* option turned off and then on. Take also into account in your runs the *branch predictor* alternatives: *none*, *static – predict always not taken* and *static – predict always taken*, and *initial predictor state* equal to *no initial state*. Discuss the results.

Original code

```
.data
values: .word 1,2,3,4,5,6,7,8,9,10      ; values to be added
nelem:  .word 10                        ; array size
sum:    .space 4                        ; sum of the array elements
.text
.global main
main:
    addi r1,r0,nelem      ; r1 = add(nelem)
    lw   r1,0(r1)         ; r1 = val(nelem)
    addi r2,r0,values     ; r2 = add(values[0])
    addi r3,r0,0          ; r3 = sum = 0 (partial sum of
                        ; the array elements)
    addi r4,r0,0          ; r4 = i = 0 (counting variable)
loop:
    lw   r5,0(r2)         ; r5 = val(values[i])
    add  r3,r3,r5         ; r3 = sum + val(values[i])
    addi r4,r4,1          ; r4 = i = i + 1
    addi r2,r2,4          ; r2 = add(values[i])
    sub  r7,r1,r4         ; r7 = val(nelem) - i
    bnez r7,loop          ; are all array elements summed?
    addi r6,r0,sum        ; r6 = add(sum)
    sw   0(r6),r3         ; save sum of the array elements
    trap 0                ; end of program
```

Due to data hazards and a control hazard, the program will not run correctly. To see why the clock cycle diagram of the execution in a processor with the five-stage pipeline architecture depicted in the guide.

	Clock cycle																	
Instruction	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
addi r1,r0,nelem	IF	ID	EX	MEM	WB													
lw r1,0(r1)		IF	ID	EX	MEM	WB												
addi r2,r0,values			IF	ID	EX	MEM	WB											
addi r3,r0,0				IF	ID	EX	MEM	WB										
addi r4,r0,0					IF	ID	EX	MEM	WB									
lw r5,0(r2)						IF	ID	EX	MEM	WB								
add r3,r3,r5							IF	ID	EX	MEM	WB							
addi r4,r4,1								IF	ID	EX	MEM	WB						
addi r2,r2,4									IF	ID	EX	MEM	WB					
sub r7,r1,r4										IF	ID	EX	MEM	WB				
bnez r7,loop											IF	ID	EX	MEM	WB			
addi r6,r0,sum												IF	ID	EX	MEM	WB		
sw 0(r6),r3													IF	ID	EX	MEM	WB	
trap 0														IF	ID	EX	MEM	WB

By interspersing nop instructions in the code, the program can be made to work correctly. One should notice that the DLX processor asserts the branching condition and computes the target address only at the *execution / effective address* stage (EX) and not at the *instruction decode / register fetch* stage (ID) as in the example discussed at the lectures. Therefore, if the branch is taken, the PC is updated at the clock cycle corresponding to the *memory access* stage (MEM) of the branch instruction (three time delays are required).

Code with `nop` instructions interspersed to make it run as intended

```

        .data
values:  .word  1,2,3,4,5,6,7,8,9,10          ; values to be added
nelem:   .word  10                          ; array size
sum:     .space  4                          ; sum of the array elements
        .text
        .global main
main:    addi    r1,r0,nelem                  ; r1 = add(nelem)
        nop
        nop
        lw      r1,0(r1)                    ; r1 = val(nelem)
        addi    r2,r0,values                 ; r2 = add(values[0])
        addi    r3,r0,0                     ; r3 = sum = 0 (partial sum of
        ;                               the array elements)
loop:    addi    r4,r0,0                     ; r4 = i = 0 (counting variable)
        lw      r5,0(r2)                    ; r5 = val(values[i])
        nop
        nop
        add     r3,r3,r5                    ; r3 = sum + val(values[i])
        addi    r4,r4,1                     ; r4 = i = i + 1
        addi    r2,r2,4                     ; r2 = add(values[i])
        nop
        sub     r7,r1,r4                    ; r7 = val(nelem) - i
        nop
        nop
        bnez    r7,loop                    ; are all array elements summed?
        nop
        nop
        nop
        addi    r6,r0,sum                    ; r6 = add(sum)
        nop
        nop
        sw      0(r6),r3                    ; save sum of the array elements
        trap 0                               ; end of program

```

It takes 156 clock cycles to run the program.

The program can be run faster if some instruction reordering is carried out. In fact, the number of interspersed `nop` instructions can be reduced from 12 to 5 and the program then runs in 122 clock cycles. Try to find out how to do that.

With the *forwarding* option turned on, most of the `nop` instructions can be removed.

```

.data
values: .word 1,2,3,4,5,6,7,8,9,10      ; values to be added
nelem:  .word 10                        ; array size
sum:    .space 4                        ; sum of the array elements
.text
.global main
main:   addi r1,r0,nelem                ; r1 = add(nelem)
        lw   r1,0(r1)                  ; r1 = val(nelem)
        addi r2,r0,values               ; r2 = add(values[0])
        addi r3,r0,0                   ; r3 = sum = 0 (partial sum of
                                     ; the array elements)
loop:   addi r4,r0,0                    ; r4 = i = 0 (counting variable)
        lw   r5,0(r2)                  ; r5 = val(values[i])
        nop
        add  r3,r3,r5                  ; r3 = sum + val(values[i])
        addi r4,r4,1                   ; r4 = i = i + 1
        addi r2,r2,4                   ; r2 = add(values[i])
        sub  r7,r1,r4                  ; r7 = val(nelem) - i
        bnez r7,loop                  ; are all array elements summed?
        nop
        nop
        addi r6,r0,sum                 ; r6 = add(sum)
        sw   0(r6),r3                 ; save sum of the array elements
        trap 0                        ; end of program

```

It takes 102 clock cycles to run the program. The version where instruction reordering is carried out, takes 92 clock cycles.

Taking into account now branch prediction, one notices that the DLX simulator considers the *branch predictor* alternatives *none* and *static – predict always not taken* as the same. So the alternative *static – predict always not taken* is the default.

Changing the *branch predictor* alternative to *static – predict always taken*, it takes 95 clock cycles to run the program; 85 clock cycles for the instruction reordered version.

One should look carefully to the clock cycle diagram of the execution to understand what is the difference between the two alternatives.