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Mestrado Integrado em Engenharia de Computadores e Telemática Arquitectura de Computadores Avançada

DLX - Pipelining 2

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Adaptation of exercise guide by Nuno Lau/José Luís Azevedo

4. Write a program that orders the values of an integer array stored in memory from the largest value to the smallest one.

Original code

```
.data
values:
            .word
                     1,2,3,4,5,6,7,8,9,10
                                                   ; values to be ordered
nelem:
            .word
                     10
                                                              ; array size
            .text
             .global main
main:
             addi
                     r1, r0, nelem
                                     ; r1 = add(nelem)
             lw
                      r1,0(r1)
                                      ; r1 = val(nelem)
                      r2,r0,values
             addi
                                      ; r2 = add(values[0])
                      r3,r0,r0
                                      ; r3 = i = 0 (counting variable)
             add
                      r8, r1, -1
                                      ; r8 = nelem - 1
             addi
                      r9,r3,r8
loop1:
             slt
                                      ; r9 = (i < nelem - 1)
                      r9,end
                                       ; is the end of operations been
             beqz
                                       ; reached?
                                      ; r6 = add(values[j])
             addi
                      r6,r2,4
             lw
                      r4,0(r2)
                                      ; r4 = val(values[i])
             addi
                      r5, r3, 1
                                       ; r5 = j = i+1 (counting variable)
loop2:
             lw
                      r7,0(r6)
                                       ; r7 = val(values[i])
             slt
                      r9, r4, r7
                                       ; r9 =
                                      ; (val(values[i]) < val(values[j]))</pre>
                      r9,qoon
                                      ; no element swap is required?
             beaz
             add
                      r9, r4, r0
                                      ; r9 = tmp = val(values[i])
             add
                      r4, r7, r0
                                      ; val(values[i]) = val(values[j])
             add
                      r7, r9, r0
                                      ; val(values[j]) = tmp
             SW
                      0(r2), r4
                                      ; val(values[i]) = r4
                      0(r6), r7
                                      ; val(values[j]) = r7
             SW
                      r5, r5, 1
                                      ; j = j + 1
qoon:
             addi
                      r6,r6,4
                                       ; r6 = add(values[j])
             addi
             slt
                      r9, r5, r1
                                       ; r9 = (j < nelem)
                      r9,100p2
                                       ; are still elements to be
             bnez
                                       ; compared?
                      r3,r3,1
             addi
                                       ; i = i + 1
                                       ; r2 = add(values[i])
                      r2,r2,4
             addi
                      loop1
                                       ; check for end of operations
end:
             trap
                      \cap
                                       ; end of program
```

4.1. Run the code in the DLX simulator with the *forwarding* option turned off and, through the interspersing of nop instructions to take care of the hazards, make it execute correctly. What is the number of clock cycles for the full execution? What is the speed up attained relatively to the original code being run in a non-pipelined processor with a clock cycle time five times longer? Take into consideration that in the latter case not all instructions take the same time to execute.

For comparing purposes, one assumes that the non-pipelined processor executes store and branch/jump instructions in 4 equivalent clock cycles and all other instructions in 5 equivalent clock cycles of the pipelined processor.

Code with nop instructions interspersed to make it run as intended

```
.data
           .word
values:
                   1,2,3,4,5,6,7,8,9,10 ; values to be ordered
           .word
nelem:
                   10
                                                         ; array size
            .text
            .global main
main:
            addi
                  r1,r0,nelem; r1 = add(nelem)
            nop
            nop
                                    ; r1 = val(nelem)
            lw
                    r1,0(r1)
                                   ; r2 = add(values[0])
             addi
                    r2,r0,values
                    r3,r0,r0
                                    ; r3 = i = 0 (counting variable)
             add
             addi
                    r8, r1, -1
                                    ; r8 = nelem - 1
            nop
            nop
                                  ; r9 = (i < nelem - 1)
loop1:
                    r9,r3,r8
            slt
            nop
            nop
                                    ; is the end of operations been
                    r9,end
            beqz
                                    ; reached?
            nop
            nop
            nop
                                  ; r6 = add(values[j])
                    r6,r2,4
            addi
                    r4,0(r2)
                                   ; r4 = val(values[i])
            lw
            addi
                    r5,r3,1
                                   ; r5 = j = i+1 (counting variable)
loop2:
                    r7,0(r6)
                                   ; r7 = val(values[j])
            lw
            nop
            nop
             slt
                    r9,r4,r7
                                   ; r9 =
                                    ; (val(values[i]) < val(values[j]))</pre>
            nop
            nop
             beqz
                    r9,goon
                                   ; no element swap is required?
             nop
             nop
             nop
             add
                    r9,r4,r0
                                   ; r9 = tmp = val(values[i])
            add
                    r4,r7,r0
                                   ; val(values[i]) = val(values[j])
            add
                    r7,r9,r0
                                    ; val(values[j]) = tmp
            nop
                    0(r2),r4
                                   ; val(values[i]) = r4
             SW
            nop
                    0(r6),r7
                                    ; val(values[j]) = r7
            SW
goon:
            addi
                    r5, r5, 1
                                    ; j = j + 1
            nop
             addi
                    r6,r6,4
                                   ; r6 = add(values[j])
             slt
                    r9, r5, r1
                                    ; r9 = (j < nelem)
            nop
            nop
                                    ; are still elements to be
            bnez
                    r9,100p2
                                     ; compared?
            nop
            nop
            nop
                                    ; i = i + 1
             addi
                    r3,r3,1
                                   ; r2 = add(values[i])
             addi
                    r2,r2,4
                                    ; check for end of operations
                    loop1
             j
            nop
             nop
             nop
                     0
                                   ; end of program
end:
            trap
```

Putting aside the nop instructions, 620 instructions are executed in 1380 clock cycles

instruction count =
$$5 + 8 \cdot 9 + 12 \cdot \sum_{i=1}^{9} i + 3 =$$

= $5 + 72 + 540 + 3 = 620$
instruction count_{store} = $2 \cdot \sum_{i=1}^{9} i = 90$
instruction count_{br/jmp} = $2 \cdot 9 + 2 \cdot \sum_{i=1}^{9} i + 1 =$
= $18 + 90 + 1 = 109$.

Thus, the equivalent number of clock cycles for the non-pipelined processor is

clock cycles_{nonpipe} = (instruction count_{store} + instruction count_{br/jmp}) · 4 +
$$+ instruction countother · 5 =$$

$$= 199 · 4 + 421 · 5 = 2901$$

and the speed up is given by

speed up =
$$\frac{\text{clock cycles}_{nonpipe}}{\text{clock cycles}_{pipe}} = \frac{2901}{1380} = 2,10$$
.

4.2. Turn the *forwarding* option on and discard the nop instructions that are no longer required. What was the speed up now attained?

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 ordered
nelem:
           .word
                                                        ; array size
           .text
           .global main
            addi
main:
                   r1,r0,nelem; r1 = add(nelem)
                                  ; r1 = val(nelem)
            lw
                   r1,0(r1)
                   r2,r0,values; r2 = add(values[0])
            addi
            add
                    r3,r0,r0
                                   ; r3 = i = 0 (counting variable)
                   r8,r1,-1
                                   ; r8 = nelem - 1
            addi
                   r9,r3,r8
                                   ; r9 = (i < nelem - 1)
loop1:
            slt
                   r9,end
                                   ; is the end of operations been
            beqz
                                   ; reached?
            nop
            nop
                                  ; r6 = add(values[j])
                    r6,r2,4
            addi
                    r6, r2, .
r4, 0 (r2)
                                   ; r4 = val(values[i])
            lw
                                   ; r5 = j = i+1 (counting variable)
                    r5,r3,1
            addi
                    r7,0(r6)
                                   ; r7 = val(values[j])
loop2:
            lw
            nop
                   r9,r4,r7
                                  ; r9 =
            slt
                                   ; (val(values[i]) < val(values[j]))</pre>
            beqz
                   r9,qoon
                                  ; no element swap is required?
            nop
            nop
                    r9,r4,r0
                                  ; r9 = tmp = val(values[i])
            add
                    r4,r7,r0
                                  ; val(values[i]) = val(values[j])
            add
            add
                    r7,r9,r0
                                  ; val(values[j]) = tmp
                    0(r2),r4
                                  ; val(values[i]) = r4
            SW
                    0(r6),r7
                                  ; val(values[j]) = r7
            SW
            addi r5, r5, 1
goon:
                                  ; j = j + 1
            addi
                   r6,r6,4
                                  ; r6 = add(values[j])
                  r9,r5,r1
            slt
                                  ; r9 = (j < nelem)
            bnez
                   r9,100p2
                                  ; are still elements to be
                                  ; compared?
            nop
            nop
                    r3,r3,1
                                 ; i = i + 1
            addi
            addi
                    r2,r2,4
                                  ; r2 = add(values[i])
                    loop1
                                  ; check for end of operations
            j
            nop
            nop
end:
                                   ; end of program
            trap
```

Taking into account now branch prediction, one has for *branch predictor* alternatives *none* or *static – predict always not taken*, which are the same for the DLX simulator, 620 instructions executed in 887 clock cycles yielding a speed up of

speed up =
$$\frac{\text{clock cycles}_{nonpipe}}{\text{clock cycles}_{pipe-nottaken}} = \frac{2901}{887} = 3,27$$
.

On the other hand, for the *branch predictor* alternative *static – predict always taken*, there is no difference in this case.

4.3. Turn on the MIPS compatibility mode, in order to enable *pipeline interlocking*, and discard the remaining nop instructions. Check that your initial code now runs correctly. Go through the clock cycle diagram to understand why. Explain what has happened in your own words. What is the speed up now attained?

With the MIPS compatibility mode now turned on, not only all the nop instructions can be removed, but also one can take advantage of the branch delay slot feature.

```
.data
                   1,2,3,4,5,6,7,8,9,10
values:
                                                 ; values to be ordered
            .word
nelem:
            .word
                   10
                                                           ; array size
            .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])
             add
                    r3,r0,r0
                                    ; r3 = i = 0 (counting variable)
             addi
                    r8, r1, -1
                                    ; r8 = nelem - 1
loop1:
                    r9,r3,r8
                                    ; r9 = (i < nelem - 1)
             slt
                                     ; is the end of operations been
            beqz
                    r9,end
                                     ; reached?
             addi
                    r6,r2,4
                                    ; r6 = add(values[j])
             lw
                    r4,0(r2)
                                    ; r4 = val(values[i])
             addi
                    r5,r3,1
                                    ; r5 = j = i+1 (counting variable)
                     r7,0(r6)
                                    ; r7 = val(values[j])
             lw
                                    ; r9 =
loop2:
                    r9,r4,r7
             slt
                                    ; (val(values[i]) < val(values[j]))
                    r9,goon
            beqz
                                    ; no element swap is required?
                    r9,r4,r0
             add
                                    ; r9 = tmp = val(values[i])
                    r4,r7,r0
                                    ; val(values[i]) = val(values[j])
             add
                     r7,r9,r0
             add
                                    ; val(values[j]) = tmp
                     0(r2),r4
             SW
                                    ; val(values[i]) = r4
                     0(r6), r7
             SW
                                    ; val(values[j]) = r7
                    r5, r5, 1
goon:
             addi
                                    ; j = j + 1
                    r6,r6,4
             addi
                                    ; r6 = add(values[j])
             slt
                     r9, r5, r1
                                    ; r9 = (j < nelem)
             bnez
                    r9,loop2
                                    ; are still elements to be
                                    ; compared?
             lw
                     r7,0(r6)
                                    ; r7 = val(values[j])
             addi
                     r3,r3,1
                                    ; i = i + 1
                     loop1
                                    ; check for end of operations
             j
             addi
                     r2, r2, 4
                                    ; r2 = add(values[i])
                                    ; end of program
end:
             trap 0
```

4.4. Consider the *branch predictor* alternatives: *none*, *static* – *predict always not taken* and *static* – *predict always taken*. Which one produces the most efficient run? Why? What is the speed up now attained?

In this case, both alternatives *static – predict always not taken* and *static – predict always taken* produce the same result: 620 instructions are executed in 689 clock cycles, yielding a speed up of

speed up =
$$\frac{\text{clock cycles}_{nonpipe}}{\text{clock cycles}_{pipe}} = \frac{2901}{689} = 4.21$$
.