Pipeline architecture: example 2



E. Sanchez, M. Sonza Reorda Politecnico di Torino

Dipartimento di Automatica e Informatica (DAUIN)

Torino - Italy

This work is licensed under the Creative Commons (CC BY-SA) License. To view a copy of this license, visit http://creativecommons.org/licenses/by-sa/3.0/



Example 2

Let consider the following pseudo-code:

```
for (i = 0; i < 100; i++) {
            Y[i] = X[i]<sup>2</sup> + X[i] / Z[i]
}
```

Suppose that

- vectors X[i] and Z[i] contain each 100 FP numbers
- were previously saved in memory
- $Z[i] \neq 0$.

Assume the following MIPS64 architecture:

- Integer ALU: 1 clock cycle
- Data memory: 1 clock cycle
- FP multiplier unit: pipelined 4 stages
- FP arithmetic unit: pipelined 2 stages
- FP divider unit: not pipelined unit, requiring 4 clock cycles
- branch delay slot: 1 clock cycle
- forwarding is enabled.

.data

vetX: .double 2, 4, 6, 8...

vetZ: .double 1, 2, 3, 4...

vetY: .double 0, 0, 0, 0...

text

MAIN: daddui R1,R0,100

daddui R2,R0,vetX

daddui R3,R0,vetZ

daddui R4,R0,vetY

loop: I.d F1,0(R2)

I.d F2,0(R3)

mul.d F3,F1,F1

div.d F4,F1,F2

add.d F5,F3,F4

s.d F5,0(R4)

daddi R2,R2,8

daddi R3,R3,8

daddi R4,R4,8

daddi R1,R1,-1

bnez R1,loop

halt

Let consider the assembly code on the left, implementing the considered C code.

Example 2 – [cont]

- 1. show the timing of the proposed loop-based program and compute the number of clock cycles this program requires to execute
- 2. using static optimization techniques, re-write the developed code in order to reduce the impact of data hazards
- 3. compute how many clock cycles the new program takes to execute.

1)

| | .text | | СС |
|-------|--------|------------|----|
| MAIN: | daddui | R1,R0,100 | |
| | daddui | R2,R0,vetX | |
| | daddui | R3,R0,vetZ | |
| | daddui | R4,R0,vetY | |
| loop: | l.d | F1,0(R2) | |
| | l.d | F2,0(R3) | |
| | mul.d | F3,F1,F1 | |
| | div.d | F4,F1,F2 | |
| | add.d | F5,F3,F4 | |
| | s.d | F5,0(R4) | |
| | daddi | R2,R2,8 | |
| | daddi | R3,R3,8 | |
| | daddi | R4,R4,8 | |
| | daddi | R1,R1,-1 | |
| | bnez | R1,loop | |
| | halt | | |

1)

| | | | СС | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-------|--------|------------|----|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|-----|----|---|---|
| MAIN: | daddui | R1,R0,25 | 5 | F | D | Е | М | W | | | | | | | | | | | | | | | | | | | | | |
| | daddui | R2,R0,vetX | 1 | | F | D | Е | М | W | | | | | | | | | | | | | | | | | | | | |
| | daddui | R3,R0,vetZ | 1 | | | F | D | Е | М | W | | | | | | | | | | | | | | | | | | | |
| | daddui | R4,R0,vetY | 1 | | | | F | D | Е | М | W | | | | | | | | | | | | | | | | | | |
| loop: | l.d | F1,0(R2) | 1 | | | | | F | D | Е | М | W | | | | | | | | | | | | | | | | | |
| | l.d | F2,0(R3) | 1 | | | | | | F | D | Е | М | W | | | | | | | | | | | | | | | | |
| | mul.d | F3,F1,F1 | 4 | | | | | | | F | D | Е | Е | Е | Е | М | W | | | | | | | | | | | | |
| | div.d | F4,F1,F2 | 1 | | | | | | | | F | D | Е | Е | Е | Е | М | W | | | | | | | | | | | |
| | add.d | F5,F3,F4 | 2 | | | | | | | | | F | D | s | S | s | E | E | М | W | | | | | | | | | |
| | s.d | F5,0(R4) | 1 | | | | | | | | | | F | s | S | s | D | s | Е | М | W | | | | | | | | |
| | daddi | R2,R2,8 | 1 | | | | | | | | | | | | | | F | S | D | E | М | W | | | | | | | |
| | daddi | R3,R3,8 | 1 | | | | | | | | | | | | | | | | F | D | E | М | W | | | | | | |
| | daddi | R4,R4,8 | 1 | | | | | | | | | | | | | | | | | F | D | E | М | W | | | | | |
| | daddi | R1,R1,-1 | 1 | | | | | | | | | | | | | | | | | | F | D | Е | М | W | | | | |
| | bnez | R1,loop | 2 | | | | | | | | | | | | | | | | | | | F | s | D | Е | М | W | | |
| | Dilez | 1.1,100μ | 1 | | | | | | | | | | | | | | | | | | | - | 3 | F | _ | IVI | VV | | |
| | | | 1 | | | | | | | | | | | | | | | | | | | | | F | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | F | D | Е | М | W |

1)

| | .text | | CC |
|-------|--------|------------|----|
| MAIN: | daddui | R1,R0,100 | 5 |
| | daddui | R2,R0,vetX | 1 |
| | daddui | R3,R0,vetZ | 1 |
| | daddui | R4,R0,vetY | 1 |
| loop: | l.d | F1,0(R2) | 1 |
| | l.d | F2,0(R3) | 1 |
| | mul.d | F3,F1,F1 | 4 |
| | div.d | F4,F1,F2 | 1 |
| | add.d | F5,F3,F4 | 2 |
| | s.d | F5,0(R4) | 1 |
| | daddi | R2,R2,8 | 1 |
| | daddi | R3,R3,8 | 1 |
| | daddi | R4,R4,8 | 1 |
| | daddi | R1,R1,-1 | 1 |
| | bnez | R1,loop | 2 |
| | | | 1 |

8 + 17 x 100

1708 ccs

17

| | .text | |
|-------|--------|------------|
| MAIN: | daddui | R1,R0,100 |
| | daddui | R2,R0,vetX |
| | daddui | R3,R0,vetZ |
| | daddui | R4,R0,vetY |
| loop: | l.d | F1,0(R2) |
| | l.d | F2,0(R3) |
| | mul.d | F3,F1,F1 |
| | div.d | F4,F1,F2 |
| | add.d | F5,F3,F4 |
| | s.d | F5,0(R4) |
| | daddi | R2,R2,8 |
| | daddi | R3,R3,8 |
| | daddi | R4,R4,8 |
| | daddi | R1,R1,-1 |
| | bnez | R1,loop |
| | halt | |

| | | | СС |
|-------|--------|------------|----|
| MAIN: | daddui | R1,R0,25 | |
| | daddui | R2,R0,vetX | |
| | daddui | R3,R0,vetZ | |
| | daddui | R4,R0,vetY | |
| loop: | l.d | F1,0(R2) | |
| | l.d | F2,0(R3) | |
| | mul.d | F3,F1,F1 | |
| | div.d | F4,F1,F2 | |
| | daddi | R2,R2,8 | |
| | add.d | F5,F3,F4 | |
| | s.d | F5,0(R4) | |
| | daddi | R3,R3,8 | |
| | daddi | R4,R4,8 | |
| | | | |

3) anticipating daddi

| | | | СС | | | | | | | | | | | | | | |
|-------|--------|------------|----|---|---|---|---|---|---|---|---|--|--|--|--|--|--|
| MAIN: | daddui | R1,R0,100 | 5 | F | D | Е | М | W | | | | | | | | | |
| | daddui | R2,R0,vetX | 1 | | F | D | Е | М | W | | | | | | | | |
| | daddui | R3,R0,vetZ | 1 | | | F | D | Е | M | W | | | | | | | |
| | daddui | R4,R0,vetY | 1 | | | | F | D | Е | M | W | | | | | | |
| loop: | l.d | F1,0(R2) | | | | | | | | | | | | | | | |
| | l.d | F2,0(R3) | | | | | | | | | | | | | | | |
| | mul.d | F3,F1,F1 | | | | | | | | | | | | | | | |
| | div.d | F4,F1,F2 | | | | | | | | | | | | | | | |
| | daddi | R2,R2,8 | | | | | | | | | | | | | | | |
| | add.d | F5,F3,F4 | | | | | | | | | | | | | | | |
| | s.d | F5,0(R4) | | | | | | | | | | | | | | | |
| | daddi | R3,R3,8 | | | | | | | | | | | | | | | |
| | daddi | R4,R4,8 | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

3) anticipating daddi

| | | | СС | | | | | | | | | | | | | | | | | | | | |
|-------|--------|------------|----|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAIN: | daddui | R1,R0,100 | 5 | F | D | Е | М | W | | | | | | | | | | | | | | | |
| | daddui | R2,R0,vetX | 1 | | F | D | Е | М | W | | | | | | | | | | | | | | |
| | daddui | R3,R0,vetZ | 1 | | | F | D | Е | M | W | | | | | | | | | | | | | |
| | daddui | R4,R0,vetY | 1 | | | | F | D | Е | М | W | | | | | | | | | | | | |
| loop: | l.d | F1,0(R2) | 1 | | | | | F | D | Е | М | W | | | | | | | | | | | |
| | l.d | F2,0(R3) | 1 | | | | | | F | D | E | М | W | | | | | | | | | | |
| | mul.d | F3,F1,F1 | 4 | | | | | | | F | D | Е | E | Е | Е | M | W | | | | | | |
| | div.d | F4,F1,F2 | 1 | | | | | | | | F | D | Е | Е | Е | Е | М | W | | | | | |
| | daddi | R2,R2,8 | 0 | | | | | | | | | F | D | Е | М | W | | | | | | | |
| | add.d | F5,F3,F4 | 2 | | | | | | | | | | F | D | S | S | Е | Е | М | W | | | |
| | s.d | F5,0(R4) | 1 | | | | | | | | | | | F | S | S | D | Е | S | М | W | | |
| | daddi | R3,R3,8 | 1 | | | | | | | | | | | | | | F | D | S | Е | М | W | |
| | daddi | R4,R4,8 | 1 | | | | | | | | | | | | | | | F | S | D | Е | M | W |
| | | | 12 | | | | | | | | | | | | | | | | | | | | |

3+) loop unrolling

| | | | СС |] | l.d | F1,0(R2) | 1 | |
|-------|--------|------------------------|----|------------|-------|----------|---|---------------|
| MAIN: | daddui | R1,R0, <mark>25</mark> | 5 | <u> </u> | l.d | F2,0(R3) | 1 | |
| | daddui | R2,R0,vetX | 1 | | mul.d | F3,F1,F1 | 4 | |
| | daddui | R3,R0,vetZ | 1 | > 8 | div.d | F4,F1,F2 | 1 | |
| | daddui | R4,R0,vetY | 1 | | daddi | R2,R2,8 | 0 | → 12 • |
| loop: | l.d | F1,0(R2) | 1 | | add.d | F5,F3,F4 | 2 | 8 |
| | l.d | F2,0(R3) | 1 | | | | + | _ |
| | mul.d | F3,F1,F1 | 4 | | s.d | F5,0(R4) | 1 | ∤ |
| | div.d | F4,F1,F2 | 1 |] | daddi | R3,R3,8 | 1 | |
| | daddi | R2,R2,8 | 0 | ├12 | daddi | R4,R4,8 | 1 | 51 x 25 |
| | add.d | F5,F3,F4 | 2 | | | | | JIXZJ |
| | s.d | F5,0(R4) | 1 | | l.d | F1,0(R2) | 1 | |
| | daddi | R3,R3,8 | 1 | 1 | l.d | F2,0(R3) | 1 | 4000 |
| | daddi | R4,R4,8 | 1 |]] | mul.d | F3,F1,F1 | 4 | 1283 |
| | | | | | div.d | F4,F1,F2 | 1 | |
| | l.d | F1,0(R2) | 1 |] | daddi | R2,R2,8 | 0 | |
| | l.d | F2,0(R3) | 1 | | add.d | F5,F3,F4 | 2 | > 15 |
| | mul.d | F3,F1,F1 | 4 | | s.d | F5,0(R4) | 1 | |
| | div.d | F4,F1,F2 | 1 | 12 | daddi | R3,R3,8 | 1 | |
| | daddi | R2,R2,8 | 0 | ├12 | daddi | R1,R1,-1 | 1 | |
| | add.d | F5,F3,F4 | 2 | | | | | |
| | s.d | F5,0(R4) | 1 | | daddi | R4,R4,8 | 1 | |
| | daddi | R3,R3,8 | 1 |]] | bnez | R1,loop | 1 | |
| | daddi | R4,R4,8 | 1 |]/ | halt | | 1 | / |

3++) loop unrolling II

| | | | СС | |
|-------|--------|------------|----|----|
| MAIN: | daddui | R1,R0,25 | 5 |) |
| | daddui | R2,R0,vetX | 1 | 8 |
| | daddui | R3,R0,vetZ | 1 | |
| | daddui | R4,R0,vetY | 1 | J |
| loop: | l.d | F1,0(R2) | 1 | |
| | l.d | F2,0(R3) | 1 | |
| | mul.d | F3,F1,F1 | 4 | 10 |
| | div.d | F4,F1,F2 | 1 | |
| | add.d | F5,F3,F4 | 2 | |
| | s.d | F5,0(R4) | 1 | J |
| | l.d | F1,8(R2) | 1 | |
| | l.d | F2,8(R3) | 1 | |
| | mul.d | F3,F1,F1 | 4 | 10 |
| | div.d | F4,F1,F2 | 1 | |
| | add.d | F5,F3,F4 | 2 | |
| | s.d | F5,8(R4) | 1 | |

| l.d | F1,16(R2) | 1 |
|-------|------------------------|---|
| l.d | F2,16(R3) | 1 |
| mul.d | F3,F1,F1 | 4 |
| div.d | F4,F1,F2 | 1 |
| add.d | F5,F3,F4 | 2 |
| s.d | F5,16(R4) | 1 |
| l.d | F1,24(R2) | 1 |
| l.d | F2,24(R3) | 1 |
| mul.d | F3,F1,F1 | 4 |
| div.d | F4,F1,F2 | 1 |
| daddi | R2,R2,32 | 0 |
| add.d | F5,F3,F4 | 2 |
| s.d | F5,24(R4) | 1 |
| daddi | R1,R1,-1 | 1 |
| daddi | R3,R3, <mark>32</mark> | 1 |
| bnez | R1,loop | 1 |
| daddi | R4,R4, <mark>32</mark> | 1 |
| halt | | 1 |