



POLITECNICO DI MILANO

μ -LAB

High Performance Processors and Systems

Dynamic Scheduling

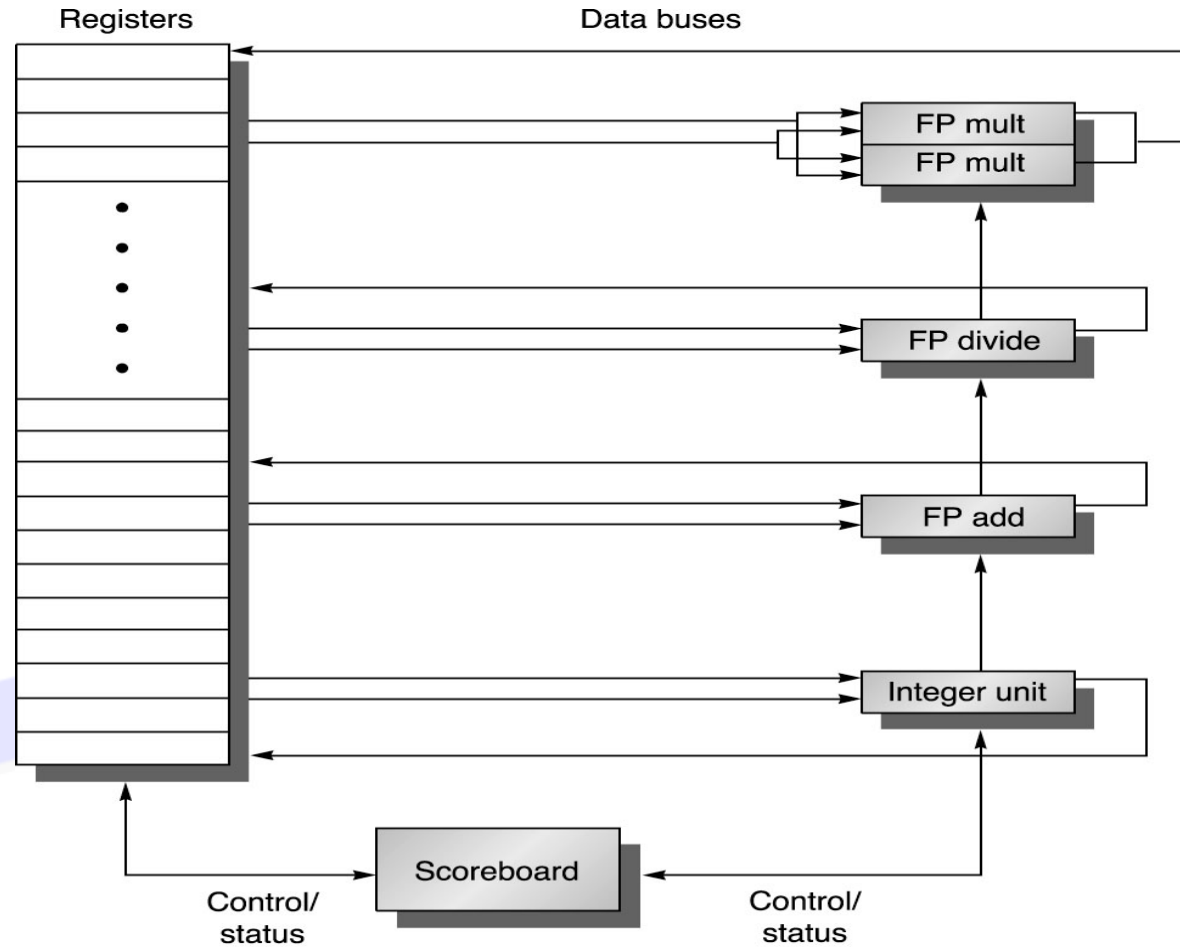
*Welcome to the world of Scoreboard and Tomasulo -
aka T&S those strangers...*

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HPPS



MIPS with Scoreboard

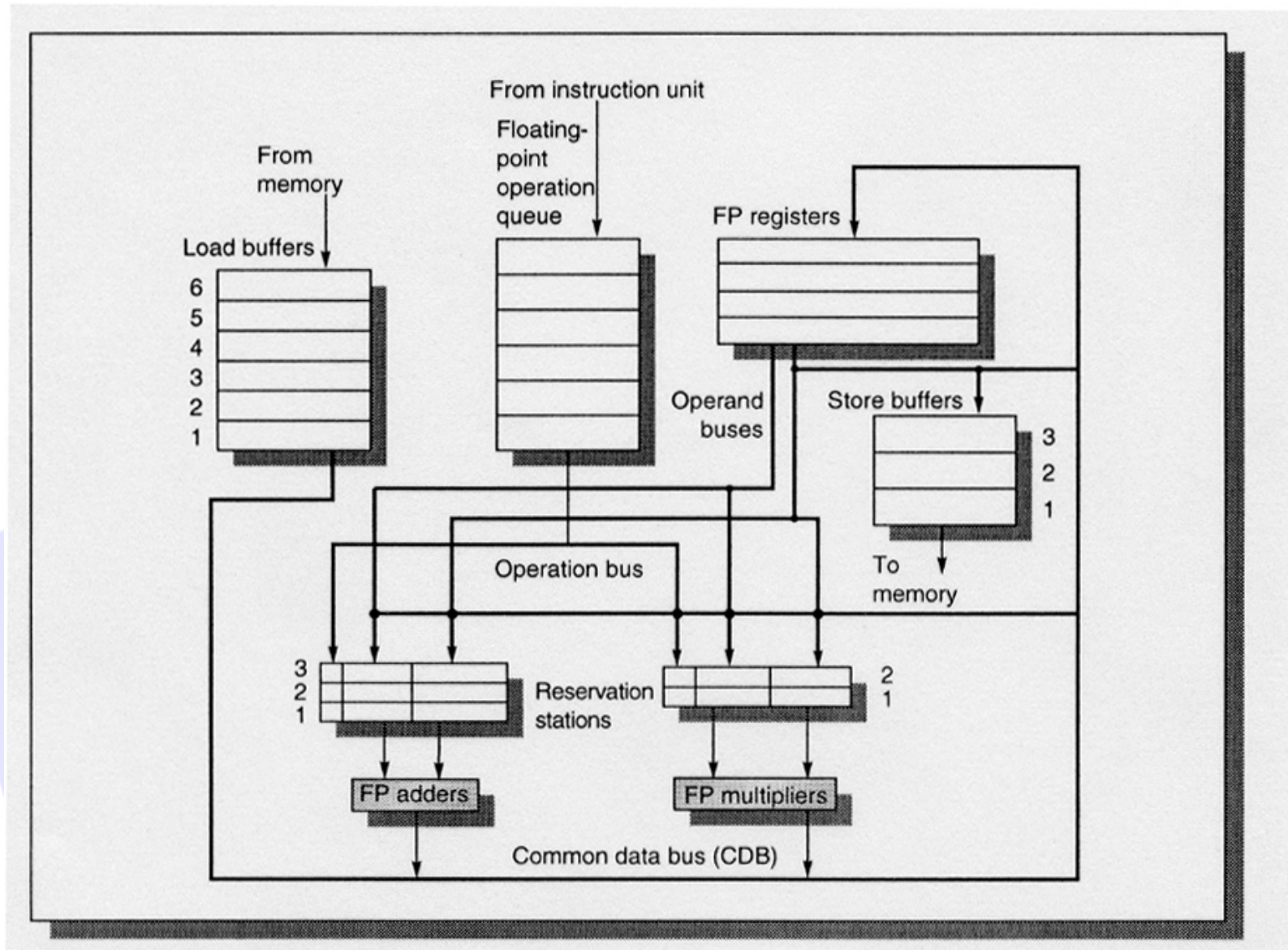


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Tomasulo Approach

INUS



RAW Conflict

S1: ADDD F0, F2, F4

S2: MULTD **F2**, F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14



Scoreboard - Clk=7

S1: ADDD F0, F2, F4

S2: MULTD **F2**, F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14

| Name | Busy | Op | Fi | Fj | Fk | Qj | Qk | Pj | Rk | Et | Ist | | | Issue | Read | Op | Exec | Co. | Write | R. |
|-------|-------|------|-----|-----|-------|-----|-----|-------|-----|----|-----|--|--|-------|------|----|------|-----|-------|----|
| Mult1 | YES | MULT | F2 | F6 | F8 | | | NO | NO | 0 | S2 | | | addd | 1 | 2 | | 4 | | 5 |
| mult2 | YES | MULT | F10 | F0 | F2 | | | MULT1 | YES | NO | S3 | | | multd | 2 | 3 | | 7 | | |
| Add1 | YES | ADD2 | F0 | F12 | F14 | | | YES | YES | 2 | S4 | | | multd | 3 | | | | | |
| Add2 | NO | | | | | | | | | | | | | addd | 6 | 7 | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | | | | | | | | | | |
| ADD1 | MULT1 | | | | MULT2 | | | | | | | | | | | | | | | |



Scoreboard - Clk=8

S1: ADDD F0, F2, F4

S2: MULTD **F2**, F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14

| Name | Busy | Op | Fi | Fj | Fk | Qj | Qk | Rj | Rk | Et | Ist | | | Issue | Read | Op | Exec | Co. | Write | R. |
|-------|------|------|-----|-----|-------|-----|-----|-----|-----|----|-----|--|--|-------|------|----|------|-----|-------|----|
| Mult1 | NO | | | | | | | | | | | | | addd | 1 | 2 | | 4 | | 5 |
| mult2 | YES | MULT | F10 | F0 | F2 | | | YES | YES | | S3 | | | multd | 2 | | 3 | | 7 | 8 |
| Add1 | YES | ADD2 | F0 | F12 | F14 | | | NO | NO | | S4 | | | multd | 3 | | | | | |
| Add2 | NO | | | | | | | | | | | | | addd | 6 | | 7 | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | | | | | | | | | | |
| ADD1 | | | | | MULT2 | | | | | | | | | | | | | | | |



Scoreboard - Clk=9

S1: ADDD F0, F2, F4

S2: MULTD **F2** F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14

| Name | Busy | Op | Fi | Fj | Fk | Qj | Qk | Rj | Rk | Et | Ist | | | Issue | Read | Op | Exec | Co. | Write | R. |
|-------|------|------|-----|-----|-------|-----|-----|-----|-----|----|-----|--|--|-------|------|----|------|-----|-------|----|
| Mult1 | NO | | | | | | | | | | | | | add | 1 | 2 | | 4 | | 5 |
| mult2 | YES | MULT | F10 | F0 | F2 | | | YES | YES | 4 | S3 | | | multd | 2 | | 3 | | 7 | 8 |
| Add1 | YES | ADD2 | F0 | F12 | F14 | | | NO | NO | 0 | S4 | | | multd | 3 | | 9 | | | |
| Add2 | NO | | | | | | | | | | | | | add | 6 | | 7 | | 9 | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | | | | | | | | | | |
| ADD1 | | | | | MULT2 | | | | | | | | | | | | | | | |



Tomasulo - Clk=6

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

| Name | Op | Vj | Vk | Qj | Qk | Etime | | Issue | Exec Co. | Write R. | |
|-------|-------|--------|--------|----|-------|-------|-----|-------|----------|----------|---|
| mult1 | MULT | R(F6) | R(F8) | | | 0 | | addd | 1 | 3 | 4 |
| mult2 | MULT | M(A1) | | | MULT1 | | | multd | 2 | 6 | |
| add1 | | | | | | | | multd | 3 | | |
| add2 | ADD | R(F12) | R(F14) | | | 0 | | addd | 4 | 6 | |
| | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | |
| ADD2 | MULT1 | | | | MULT2 | | | | | | |



Tomasulo - Clk=7

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

| Name | Op | Vj | Vk | Qj | Qk | Time | issue | Exec Co. | Write R. |
|-------|------|--------|--------|----|-------|------|-------|----------|----------|
| mult1 | | | | | | | add | 1 | 3 |
| mult2 | MULT | M(A1) | M(M1) | | ✓ | | multd | 2 | 6 |
| add1 | | | | | | | multd | 3 | |
| add2 | ADD | R(F12) | R(F14) | | | 0 | add | 4 | 6 |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | |
| ADD2 | | | | | MULT2 | | | | |



Tomasulo - Clk=8

S1: ADDD F0, F2, F4

S2: MULTD **F2**, F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14

| Name | Op | Vj | Vk | Qj | Qk | Etime | | Issue | Exec Co. | Write R. | |
|-------|------|-------|-------|----|-------|-------|-----|-------|----------|----------|---|
| mult1 | | | | | | | | addd | 1 | 3 | 4 |
| mult2 | MULT | M(A1) | M(M1) | | | 3 | | multd | 2 | 6 | 7 |
| add1 | | | | | | | | multd | 3 | | |
| add2 | | | | | | | | addd | 4 | 6 | 8 |
| | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | |
| | | | | | MULT2 | | | | | | |



Tomasulo - Clk=11

S1: ADDD F0, F2, F4

S2: MULTD **F2** F6, F8

S3: MULTD F10, F0, **F2**

S4: ADDD F0, F12, F14

Exe: 8, 9, 10, 11

| Name | Op | Vj | Vk | Qj | Qk | Etime | | Issue | Exec Co. | Write R. | |
|-------|------|-------|-------|----|-------|-------|-----|-------|----------|----------|---|
| mult1 | | | | | | | | addd | 1 | 3 | 4 |
| mult2 | MULT | M(A1) | M(M1) | | | 0 | | multd | 2 | 6 | 7 |
| add1 | | | | | | | | multd | 3 | 11 | |
| add2 | | | | | | | | addd | 4 | 6 | 8 |
| | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | |
| | | | | | MULT2 | | | | | | |

WAR Conflict

S1: ADDD F0, F2, F4
S2: MULTD F2, F6, F8
S3: MULTD F10, F0, F2
S4: ADDD F0, F12, F14



Scoreboard - Clk=9

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

S4 can complete its **exe** but it **MUST WAIT** to **WriteR**
till S3 **reads** the op

| Name | Busy | Op | Fi | Fj | Fk | Qj | Qk | Rj | Rk | Et | Ist | | | Issue | Read | Op | Exec | Co. | Write | R. |
|-------|------|------|-----|-----|-------|-----|-----|-----|-----|----|-----|--|--|-------|------|----|------|-----|-------|----|
| Mult1 | NO | | | | | | | | | | | | | add | 1 | 2 | | 4 | | 5 |
| mult2 | YES | MULT | F10 | F0 | F2 | | | YES | YES | 4 | S3 | | | multd | 2 | 3 | | 7 | | 8 |
| Add1 | YES | ADD2 | F0 | F12 | F14 | | | NO | NO | 0 | S4 | | | multd | 3 | 9 | | | | |
| Add2 | NO | | | | | | | | | | | | | add | 6 | 7 | | 9 | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | | | | | | | | | | |
| ADD1 | | | | | MULT2 | | | | | | | | | | | | | | | |



Scoreboard - Clk=10

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

| Name | Busy | Op | Fi | Fj | Fk | Qj | Qk | Rj | Rk | Et | Ist | Issue | Read | Op | Exec | Co. | Write | R. |
|-------|------|------|-----|----|-------|-----|-----|----|----|----|-----|-------|------|----|------|-----|-------|----|
| Mult1 | NO | | | | | | | | | | | add | 1 | 2 | | 4 | | 5 |
| mult2 | YES | MULT | F10 | F0 | F2 | | | NO | NO | 3 | S3 | multd | 2 | 3 | | 7 | | 8 |
| Add1 | NO | | | | | | | | | | | multd | 3 | | | | | |
| Add2 | NO | | | | | | | | | | | add | 6 | 7 | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | | | | | | | | |
| | | | | | MULT2 | | | | | | | | | | | | | |

Rj, Rk update: 10

$S_i - S_j (i < j)$: WAR

MUST: $Clk_EXE_S_j < Clk_WRITE_S_j$

If: $Clk_READ_S_i < Clk_EXE_S_j$ no prob at all

If: $Clk_READ_S_i \geq Clk_EXE_S_j$ **MUST BE:** $Clk_WRITE_S_j > Clk_READ_S_i$

$(Clk_WRITE_S_j = Clk_READ_S_i + 1)$



Tomasulo - Clk=6

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

F0 = M(A1)

F0 ≠ F0

They have the same name, but they **ARE different!!!**

| Name | Op | Vj | Vk | Qj | Qk | Etime | | Issue | Exec Co. | Write R. | |
|-------|-------|--------|--------|----|-------|-------|-----|-------|----------|----------|---|
| mult1 | MULT | R(F6) | R(F8) | | | 0 | | addd | 1 | 3 | 4 |
| mult2 | MULT | M(A1) | | | MULT1 | | | multd | 2 | 6 | |
| add1 | | | | | | | | multd | 3 | | |
| add2 | ADD | R(F12) | R(F14) | | | 0 | | addd | 4 | 6 | |
| | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | |
| ADD2 | MULT1 | | | | MULT2 | | | | | | |



Tomasulo - Clk=7

S1: ADDD F0, F2, F4

S2: MULTD F2, F6, F8

S3: MULTD F10, F0, F2

S4: ADDD F0, F12, F14

F0 = M(A1)

| Name | Op | Vj | Vk | Qj | Qk | Etime | | Issue | Exec Co. | Write R. | |
|-------|-------|-------|-------|----|-------|-------|-----|-------|----------|----------|---|
| mult1 | MULT | R(F6) | R(F8) | | | 0 | | addd | 1 | 3 | 4 |
| mult2 | MULT | M(A1) | | | MULT1 | | | multd | 2 | 6 | |
| add1 | | | | | | | | multd | 3 | | |
| add2 | | | | | | | | addd | 4 | 6 | 7 |
| | | | | | | | | | | | |
| F0 | F2 | F4 | F6 | F8 | F10 | F12 | F14 | | | | |
| | MULT1 | | | | MULT2 | | | | | | |

Tomasulo - loop

```
#include <stdio.h>
int main(void)
{
    int count;

    for (count = 1; count <= 500; count++)
        printf("I will not throw paper airplanes in class.");
    return 0;
}
```

WEND 10-3

NICE TRY.



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Tomasulo - Clk=3

Instruction status

| Instruction | <i>j</i> | <i>k</i> | <i>iteration</i> | <i>Issue</i> | <i>Execution</i> | <i>Write Result</i> | <i>Busy</i> | <i>Address</i> |
|-------------|----------|----------|------------------|--------------|------------------|---------------------|-------------|----------------|
| LD F0 | 0 | R1 | 1 | 1 | | Load1 | Yes | 80 |
| MULT F4 | F0 | F2 | 1 | 2 | | Load2 | No | |
| SD F4 | 0 | R1 | 1 | 3 | | Load3 | No | Qi |
| LD F0 | 0 | R1 | 2 | | | Store1 | Yes | 80 |
| MULT F4 | F0 | F2 | 2 | | | Store2 | No | |
| SD F4 | 0 | R1 | 2 | | | Store3 | No | |

Reservation Stations

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>S1</i> <i>Vj</i> | <i>S2</i> <i>Vk</i> | <i>RS for j</i> <i>Qj</i> | <i>RS for k</i> <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|------------------------|------------------------|------------------------------|------------------------------|---------------|
| 0 | Add1 | No | | | | | | LD F0 0 R1 |
| 0 | Add2 | No | | | | | | MULT F4 F0 F2 |
| 0 | Add3 | No | | | | | | SD F4 0 R1 |
| 0 | Mult1 | Yes | MULTD | | R(F2) | Load1 | | SUBI R1 R1 #8 |
| 0 | Mult2 | No | | | | | | BNEZ R1 Loop |

Register result status

| Clock | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12...</i> | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|---------------|------------|
| 3 | 80 | Load1 | | Mult1 | | | | | |

Tomasulo - Clk=4

| Instruction status | | | | Execution Write | | | Busy Address | |
|--------------------|----------|----------|-----------|-----------------|----------|--------|--------------|---------|
| Instruction | <i>j</i> | <i>k</i> | iteration | Issue | complete | Result | Busy | Address |
| LD F0 | 0 | R1 | 1 | 1 | | Load1 | Yes | 80 |
| MULT F4 | F0 | F2 | 1 | 2 | | Load2 | No | |
| SD F4 | 0 | R1 | 1 | 3 | | Load3 | No | Qi |
| LD F0 | 0 | R1 | 2 | | | Store1 | Yes | 80 |
| MULT F4 | F0 | F2 | 2 | | | Store2 | No | Mult1 |
| SD F4 | 0 | R1 | 2 | | | Store3 | No | |

| Reservation Stations | | | <i>S1</i> | <i>S2</i> | <i>RS for j</i> | <i>RS for k</i> | Code: |
|----------------------|-------|-----------|-----------|-----------|-----------------|-----------------|---------------|
| Time | Name | Busy Op | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | |
| 0 | Add1 | No | | | | | LD F0 0 R1 |
| 0 | Add2 | No | | | | | MULT F4 F0 F2 |
| 0 | Add3 | No | | | | | SD F4 0 R1 |
| 0 | Mult1 | Yes MULTD | | R(F2) | Load1 | | SUBI R1 R1 #8 |
| 0 | Mult2 | No | | | | | BNEZ R1 Loop |

Register result status

| Clock | R1 | F0 | F2 | F4 | F6 | F8 | F10 | F12... | F30 |
|-------|-------|-------|----|-------|----|----|-----|--------|-----|
| 4 | 72 Qi | Load1 | | Mult1 | | | | | |

Tomasulo - Clk=5

Instruction status

| Instruction | <i>j</i> | <i>k</i> | iteration | Issue | Execution | Write Back | Result | Busy | Address |
|-------------|----------|----------|-----------|-------|-----------|------------|--------|------|---------|
| LD F0 | 0 | R1 | 1 | 1 | | | Load1 | Yes | 80 |
| MULT F4 | F0 | F2 | 1 | 2 | | | Load2 | No | |
| SD F4 | 0 | R1 | 1 | 3 | | | Load3 | No | Qi |
| LD F0 | 0 | R1 | 2 | | | | Store1 | Yes | 80 |
| MULT F4 | F0 | F2 | 2 | | | | Store2 | No | |
| SD F4 | 0 | R1 | 2 | | | | Store3 | No | |

Reservation Stations

| Time | Name | Busy | Op | S1 <i>Vj</i> | S2 <i>Vk</i> | RS for <i>j</i> <i>Qj</i> | RS for <i>k</i> <i>Qk</i> | Code: |
|------|-------|------|-------|-----------------|-----------------|------------------------------|------------------------------|---------------|
| 0 | Add1 | No | | | | | | LD F0 0 R1 |
| 0 | Add2 | No | | | | | | MULT F4 F0 F2 |
| 0 | Add3 | No | | | | | | SD F4 0 R1 |
| 0 | Mult1 | Yes | MULTD | | R(F2) | Load1 | | SUBI R1 R1 #8 |
| 0 | Mult2 | No | | | | | | BNEZ R1 Loop |

Register result status

| Clock | R1 | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|-------|----|----|-------|----|-------|----|-----|-----|-----|-----|
| 5 | 72 | Qi | Load1 | | Mult1 | | | | | |

Tomasulo - Clk=6

Instruction status

| Instruction | <i>j</i> | <i>k</i> | iteration | Issue | Execution complete | Result | Busy | Address |
|-------------|----------|----------|-----------|-------|--------------------|--------|------|---------|
| LD F0 | 0 | R1 | 1 | 1 | | Load1 | Yes | 80 |
| MULT F4 | F0 | F2 | 1 | 2 | | Load2 | Yes | 72 |
| SD F4 | 0 | R1 | 1 | 3 | | Load3 | No | Qi |
| LD F0 | 0 | R1 | 2 | 6 | | Store1 | Yes | 80 |
| MULT F4 | F0 | F2 | 2 | | | Store2 | No | |
| SD F4 | 0 | R1 | 2 | | | Store3 | No | |

Reservation Stations

| Time | Name | Busy | Op | <i>S1</i> <i>Vj</i> | <i>S2</i> <i>Vk</i> | <i>RS for j</i> <i>Qj</i> | <i>RS for k</i> <i>Qk</i> | Code: |
|------|-------|------|-------|------------------------|------------------------|------------------------------|------------------------------|---------------|
| 0 | Add1 | No | | | | | | LD F0 0 R1 |
| 0 | Add2 | No | | | | | | MULT F4 F0 F2 |
| 0 | Add3 | No | | | | | | SD F4 0 R1 |
| 0 | Mult1 | Yes | MULTD | | R(F2) | Load1 | | SUBI R1 R1 #8 |
| 0 | Mult2 | No | | | | | | BNEZ R1 Loop |

Register result status

| Clock | R1 | F0 | F2 | F4 | F6 | F8 | F10 | F12... | F30 |
|-------|----|----|-------|-------|----|----|-----|--------|-----|
| 6 | 72 | Qi | Load2 | Mult1 | | | | | |



Questions

ITALIA

HPFS

