

Course on: “Advanced Computer Architectures”

Scoreboard Dynamic Scheduling Algorithm



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Recap on Dynamic Scheduling

- **Simple scalar pipeline:** Hazards due to true data dependences that cannot be solved by forwarding cause the stall of the pipeline: no new instructions can be fetched nor issued even if there are not data dependences!
 - **Solution: Allow data independent instructions behind a stall to proceed**
 - HW rearranges dynamically the instruction execution to reduce stalls
- => This enables out-of-order execution and out-of-order commit.**
- First implemented in CDC 6600 (1963).

Example of Dynamic Scheduling

```
DIVD  F0 , F2 , F4      # takes many cycles
ADDD  F10 , F0 , F8      # RAW F0
SUBD  F12 , F8 , F14
```

- RAW hazard: **ADDD** stalls for RAW hazards on **F0** (stall many cycles for **DIVD** commit).
- **SUBD** would stall even if not data dependent on anything in the pipeline.
- **BASIC IDEA:** to enable **SUBD** to proceed
=> this generates *out-of-order execution*

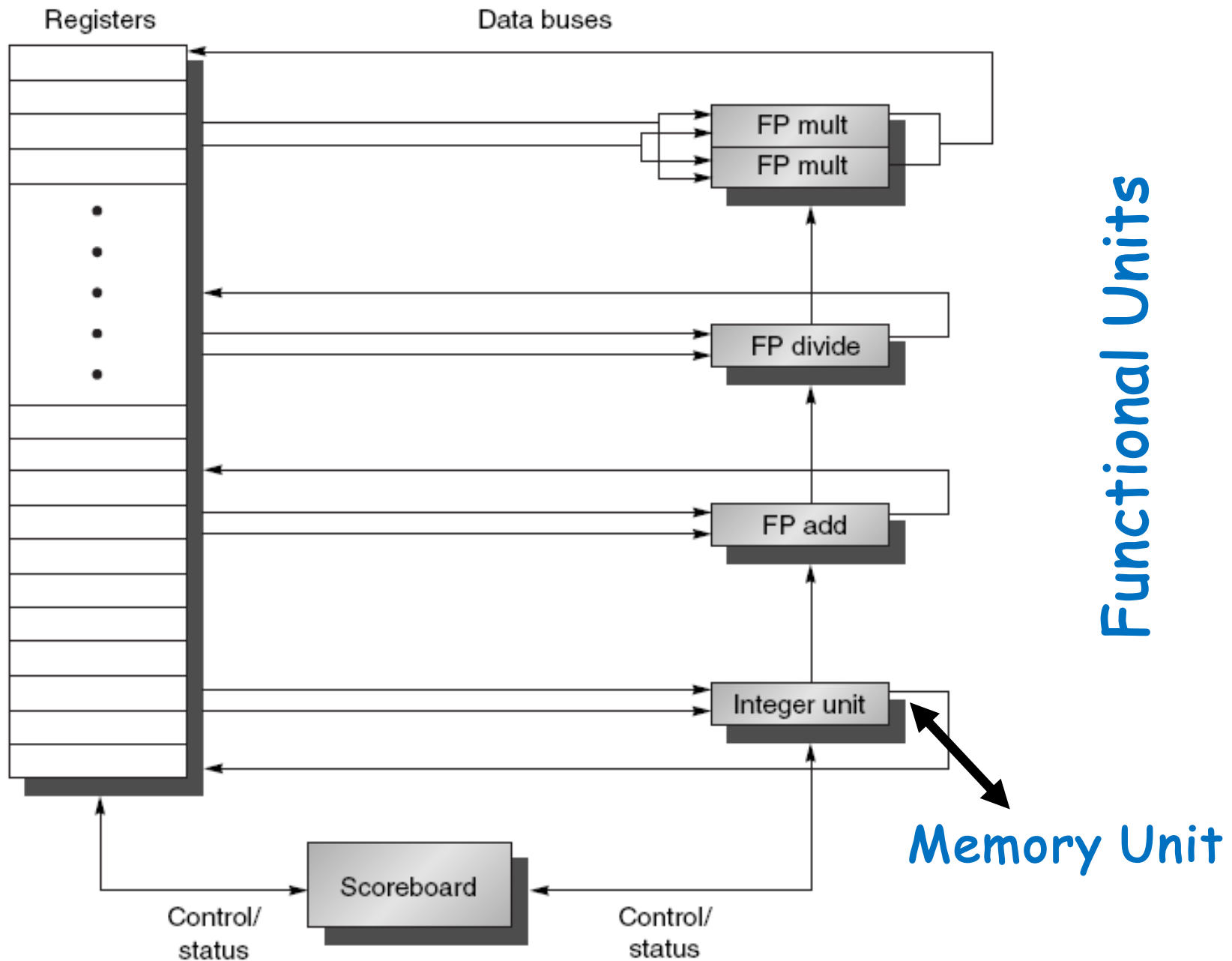
Scoreboard Basic Assumptions

- We consider a *single-issue* processor.
 - Instruction Fetch stage fetches and issues instructions in program order (*in-order issue*).
 - Instruction execution begins *as soon as operands are ready* whenever not dependent on previous instructions (*no RAW hazards*).
 - There are *multiple* pipelined Functional Units with *variable latencies*.
 - Execution stage might require *multiple cycles*, depending on the operation type and latency.
 - Memory stage might require *multiple cycles* access time due to data cache misses.
- ⇒ *Out-of-order execution & out-of-order commit*
(this introduces the possibility of **WAR** & **WAW** hazards).

Scoreboard basic scheme

- Scoreboard allows *data independent instructions behind a stall to proceed*, not waiting for prior instructions.
- We distinguish when an instruction begins execution and it completes execution: between the two times, the instruction is *in execution*.
- Scoreboard pipeline allows *multiple instructions in execution at the same time* \Rightarrow that requires multiple pipelined functional units.
- *In-order issue, out-of-order execution, out-of-order completion (commit)*
 - *No forwarding!*
 - *Imprecise interrupt/exception model for now!*

Scoreboard basic architecture



Scoreboard Pipeline Stages

- Scoreboard divides the **ID** stage in **two stages**:
 1. **Issue**—Decode instructions and check for structural hazards
 2. **Read operands (RR)**—Wait until not dependent on previous instructions and no data hazards, then read operands

Scoreboard Pipeline Stages

- Scoreboard divides the ID stage in two stages:
 1. Issue—Decode instructions and check for structural hazards
 2. Read operands (RR)—Wait until not dependent on previous instructions and no data hazards, then read operands
- Scoreboard allows instructions to execute whenever 1 & 2 hold, not waiting for prior instructions to complete.
- Scoreboard keeps track of **dependencies** and state of **parallel ongoing operations**.
- Instructions pass through the issue stage *in-order*, but they can be stalled or bypass each other in the read operand stage (*out-of-order read operands*).
- Then instructions enter execution *out-of-order* and have different latencies, which implies *out-of-order completion (commit)*.
- **Summary: In-order issue but out-of-order read-operands \Rightarrow out-of-order execution & commit.**

Scoreboard Implications

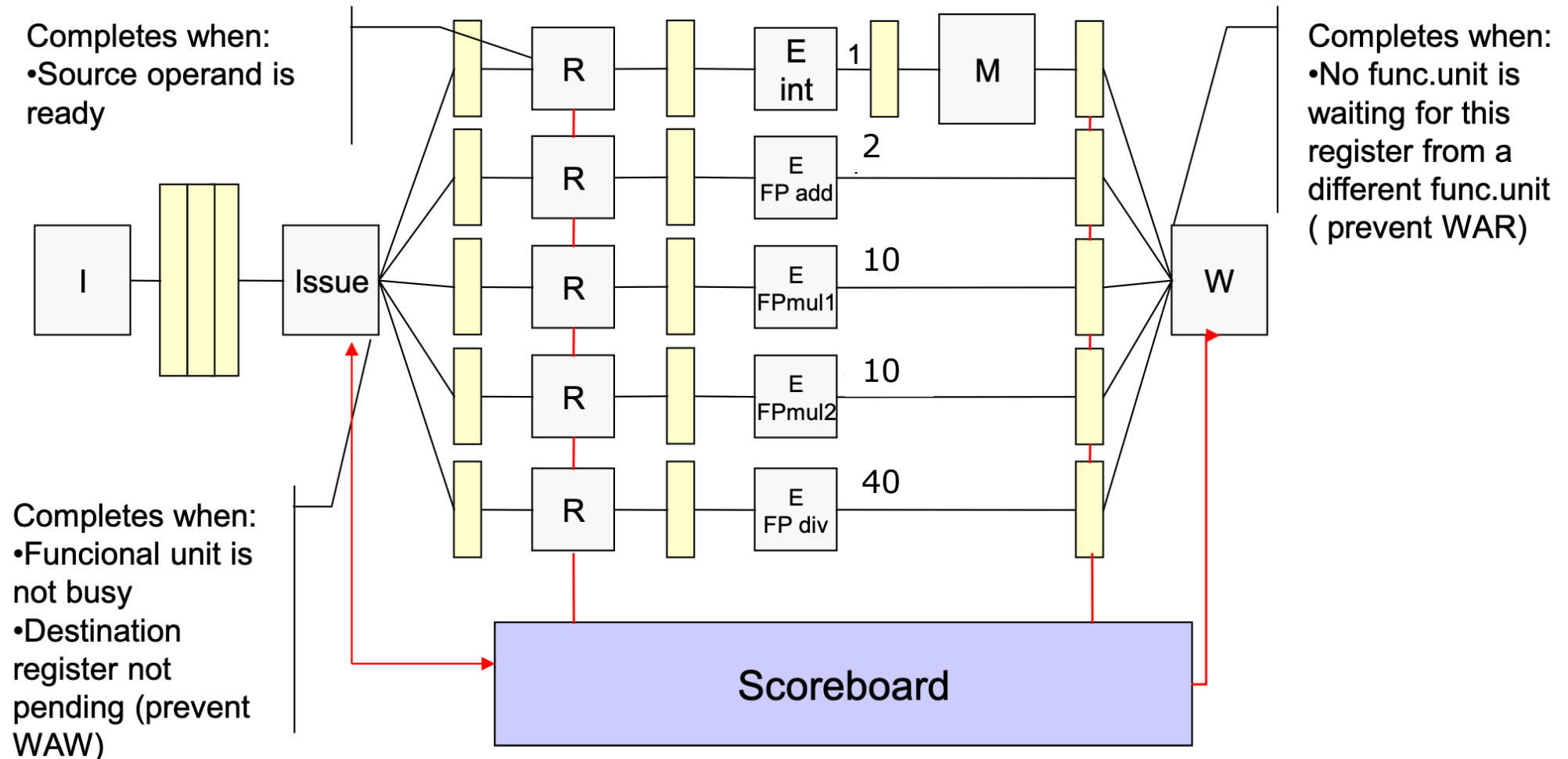
- There are multiple instructions in execution phase
→ Multiple execution units or pipelined execution units
- No register renaming (compile time technique).
- Out-of-order commit ⇒ **WAR and WAW hazards can occur**
- **Solutions for WAR:**
 - Read registers only during Read Operands stage.
 - Stall write back until previous registers have been read.
- **Solution for WAW:**
 - Detect WAW hazard and stall issue of new instruction until previous instruction causing WAW completes.

Scoreboard Scheme

- Any hazard detection and resolution is **centralized** in the Scoreboard:
 - Every instruction goes through the Scoreboard, where a record of data dependences is constructed
 - The Scoreboard then determines **when** the instruction can read its operand and begin execution (**check for RAW**)
 - If the Scoreboard decides the instruction cannot execute immediately, it monitors every change and decides **when** the instruction can execute.
 - The scoreboard controls **when** the instruction can write its result into destination register (**check for WAR & WAW**)

Scoreboard Architecture

- The idea of a scoreboard is to keep track of the status of instructions, functional units and registers



Four Stages of Scoreboard Control

1. Issue

Decode instruction and check for structural hazards & WAW hazards

Instructions issued in program order (for hazard checking)

- If a functional unit for the instruction is available (**no structural hazard**) and no other active instruction has the same destination register (**no WAW hazard**) => the Scoreboard issues the instruction to the FU and updates its data structure.
- If either a **structural hazard** or a **WAW hazard** exists => the instruction issue stalls, and no further instructions will issue until these hazards are solved.

Four Stages of Scoreboard Control

2. Read Operands

Wait until no RAW hazards => then read operands.

Check for structural hazards in reading ports of RF.

- A source operand is available if:
 - No earlier issued active instruction will write it or
 - A functional unit is writing its value in a register
- When the source operands are available, the Scoreboard tells the FU to proceed to read the operands from the RF and begin execution.
- RAW hazards are solved dynamically in this step
 - => **out-of-order** reading of operands
 - => instructions are sent into execution **out-of-order**.
- **No data forwarding**

Four Stages of Scoreboard Control

3. Execution

**The FU begins execution upon receiving operands.
When the result is ready, it notifies the Scoreboard that
execution has been completed.**

- FUs are characterized by **variable latency** to complete execution.
- **Load/Store latency depends on data cache HIT/MISS times.**

=> Out-of-order execution

Four Stages of Scoreboard Control

4. Write result

Check for WAR hazards on destination.

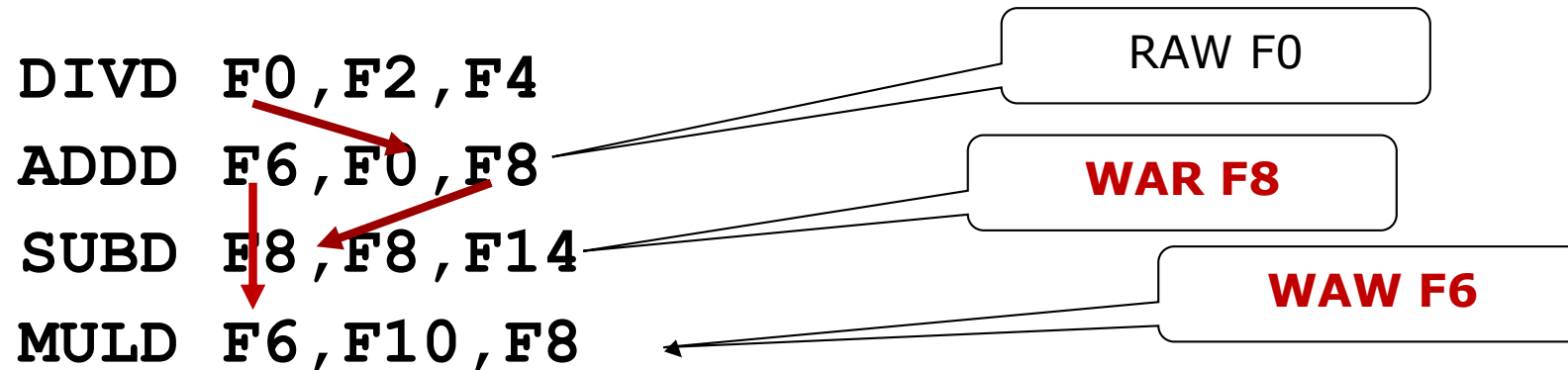
Check for structural hazards in writing RF and finish execution.

Once the Scoreboard is aware that the FU has completed execution, **the Scoreboard checks for WAR hazards.**

- If none, it writes results.
- If there is a **WAR** => the Scoreboard stalls the completing instruction.

=> Out-of-order commit

RAW/WAR/WAW Example



- To avoid the **WAR** hazard on F8, the Scoreboard would:
 - Stall **SUBD** in the WB stage, waiting for **ADDD** reads F0 and F8;
- To avoid the **WAW** hazard on F6, the Scoreboard would:
 - Stall **MULD** in the ISSUE stage until **ADDD** writes F6.
- Note: Any WAR/WAW hazard could have been solved through register renaming at compile time.

Recap: SCOREBOARD BASIC SCHEME

- IN-ORDER ISSUE
- OUT-OF-ORDER READ OPERANDS
- OUT-OF-ORDER EXECUTION
- OUT-OF-ORDER COMPLETION
- NO FORWARDING
- Control is centralized into the Scoreboard

Recap: SCOREBOARD STAGES

- **ISSUE (IN-ORDER):**
 - Check for structural hazards
 - Check for WAW hazards on destination operand (*)
- **READ OPERANDS (OUT-OF-ORDER)**
 - Check for RAW hazards
 - Check for structural hazards in reading RF
- **EXECUTION (OUT-OF-ORDER)**
 - Execution completion depends on latency of FUs
 - Execution completion of LD/ST depends on cache hit/miss latencies
- **WRITE RESULTS (OUT-OF-ORDER)**
 - Check for WAR hazards on destination operand
 - Check for structural hazards in writing RF

Recap: SCOREBOARD optimizations

(*) Optimizations:

1. Check for **WAW postponed** from **ISSUE** stage to **WRITE** stage
2. Data forwarding

Scoreboard Structure

1. Instruction status

2. Functional Unit status

Indicates the state of the functional unit (FU):

| | |
|---------------|---|
| Busy | Indicates whether the unit is busy or not |
| Op | The operation to perform in the unit (+, -, etc.) |
| Fi | Destination register |
| Fj, Fk | Source register numbers |
| Qj, Qk | Functional units producing source registers Fj, Fk |
| Rj, Rk | Flags indicating when Fj, Fk are ready. Flags are set to NO after operands are read. |

3. Register result status

Indicates which functional unit will write each register. Blank if no pending instructions will write that register.

Scoreboard Example:

Analysis of dependences and hazards

LD F6, 34 (R2)

LD F2, 45 (R3)

MULTD F0, F2, F4 # RAW F2

SUBD F8, F6, F2 # RAW F2, RAW F6

DIVD F10, F0, F6 # RAW F0, RAW F6

ADDD F6, F8, F2 # WAW F6, WAR F6,
RAW F8, RAW F2

Scoreboard Example

Instruction status:

| Instruction | | <i>j</i> | <i>k</i> | <i>Read</i> <i>Issue</i> | <i>Exec</i> <i>Oper</i> | <i>Write</i> <i>Comp</i> | <i>Result</i> |
|-------------|-----|----------|----------|-----------------------------|----------------------------|-----------------------------|---------------|
| LD | F6 | 34+ | R2 | | | | |
| LD | F2 | 45+ | R3 | | | | |
| MULTD | F0 | F2 | F4 | | | | |
| SUBD | F8 | F6 | F2 | | | | |
| DIVD | F10 | F0 | F6 | | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest</i> <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|-------------|-------------|-------------|-----------|--------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| <i>FU</i> | | | | | | | | | |

Scoreboard Example: Cycle 1

Instruction status:

| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|-----|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ | R2 | 1 | | | |
| LD | F2 | 45+ | R3 | | | | |
| MULTD | F0 | F2 | F4 | | | | |
| SUBD | F8 | F6 | F2 | | | | |
| DIVD | F10 | F0 | F6 | | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

unit status:

| | | <i>dest</i> | <i>S1</i> | <i>S2</i> | <i>FU</i> | <i>FU</i> | <i>Fj?</i> | <i>Fk?</i> | | |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|------------|------------|-----------|-----------|
| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Fi</i> | <i>Fj</i> | <i>Fk</i> | <i>Qj</i> | <i>Qk</i> | <i>Rj</i> | <i>Rk</i> |
| | Integer | Yes | Load | F6 | | R2 | | | | Yes |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 1 | <i>FU</i> | | | | Integer | | | | | |

Scoreboard Example Cycle 2

| Instruction status | | | | Read | Executi | Write |
|--------------------|----------|----------|--------------|----------------|---------------|---------------|
| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>operand</i> | <i>comple</i> | <i>Result</i> |
| LD | F6 | 34+ R2 | 1 | 2 | | |
| LD | F2 | 45+ R3 | | | | |
| MULT | F0 | F2 F4 | | | | |
| SUBD | F8 | F6 F2 | | | | |
| DIVD | F10 | F0 F6 | | | | |
| ADDD | F6 | F8 F2 | | | | |

| Functional unit status | | | <i>dest</i> | <i>S1</i> | <i>S2</i> | <i>FU for j</i> | <i>FU for k</i> | <i>Fj?</i> | <i>Fk?</i> | |
|------------------------|-------------|-------------|-------------|-----------|-----------|-----------------|-----------------|------------|------------|-----------|
| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Fi</i> | <i>Fj</i> | <i>Fk</i> | <i>Qj</i> | <i>Qk</i> | <i>Rj</i> | <i>Rk</i> |
| | Integer | Yes | Load | F6 | | R2 | | | | Yes |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

| Register result status | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|------------------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| Clock | | | | | | | | | | |
| 2 | <i>FU</i> | Integer | | | | | | | | |

Issue 2nd load? No: Integer Unit busy – Cannot issue 2nd Load due to structural hazard on Integer Unit => *Issue stalls*

Issue multiply?

Scoreboard Example Cycle 3

| <u>Instruction status</u> | | | | <i>Read</i> | <i>Executi</i> | <i>Write</i> |
|---------------------------|----------|----------|--|--------------|-----------------------|---------------|
| Instruction | <i>j</i> | <i>k</i> | | <i>Issue</i> | <i>operand comple</i> | <i>Result</i> |
| LD F6 | 34+ | R2 | | 1 | 2 | 3 |
| LD F2 | 45+ | R3 | | | | |
| MULT F0 | F2 | F4 | | | | |
| SUBD F8 | F6 | F2 | | | | |
| DIVD F10 | F0 | F6 | | | | |
| ADDD F6 | F8 | F2 | | | | |

| <u>Functional unit status</u> | | | <i>dest</i> | <i>S1</i> | <i>S2</i> | <i>FU for j</i> | <i>FU for k</i> | <i>Fj?</i> | <i>Fk?</i> | |
|-------------------------------|-------------|-------------|-------------|-----------|-----------|-----------------|-----------------|------------|------------|-----------|
| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Fi</i> | <i>Fj</i> | <i>Fk</i> | <i>Qj</i> | <i>Qk</i> | <i>Rj</i> | <i>Rk</i> |
| | Integer | Yes | Load | F6 | | R2 | | | | Yes |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

| <u>Register result status</u> | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|-------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| Clock | | | | | | | | | | |
| 3 | <i>FU</i> | Integer | | | | | | | | |

- **Issue stalls**
- **Load execution complete in one clock cycle (ideal data cache hit)**

Scoreboard Example: Cycle 4

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Issue | Read <i>Oper</i> | Exec <i>Comp</i> | Write <i>Result</i> |
|-------------|----------|----------|-------|---------------------|---------------------|------------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | | | | |
| MULTD | F0 | F2 F4 | | | | |
| SUBD | F8 | F6 F2 | | | | |
| DIVD | F10 | F0 F6 | | | | |
| ADDD | F6 | F8 F2 | | | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest</i> <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|-------------|-------------|-------------|-----------|--------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|------------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 4 | FU Integer | | | | | | | | |

- **Issue stalls**
- **Write F6 & Integer Unit no more busy**

Scoreboard Example: Cycle 5

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> |
|----------------------------|----------|----------|--------------|-------------|-------------|---------------|
| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> |
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | | | |
| MULTD | F0 | F2 F4 | | | | |
| SUBD | F8 | F6 F2 | | | | |
| DIVD | F10 | F0 F6 | | | | |
| ADDD | F6 | F8 F2 | | | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|-------------|-------------|-------------|-----------|----------------|--------------|--------------|--------------|--------------|---------------|---------------|
| | Integer | Yes | Load | F2 | | R3 | | | | Yes |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 5 | | Integer | | | | | | | |

- The second load is issued

Scoreboard Example: Cycle 6

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> | |
|----------------------------|-----|----------|----------|--------------|-------------|--------------|---------------|
| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | | |
| MULTD | F0 | F2 | F4 | 6 | | | |
| SUBD | F8 | F6 | F2 | | | | |
| DIVD | F10 | F0 | F6 | | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

| Time | Name | Busy | Op | dest <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|------|-------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | Yes | Load | F2 | | F2 | | | | Yes |
| | Mult1 | Yes | Mult | F0 | F2 | F4 | Integer | | No | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

Clock
6

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|----|-------|---------|----|----|----|-----|-----|-----|-----|
| FU | Mult1 | Integer | | | | | | | |

- MULT is issued, but it has to wait for F2 from 2nd LOAD (RAW Hazard on F2)

Scoreboard Example: Cycle 7

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> | |
|----------------------------|-----|----------|----------|--------------|-------------|--------------|---------------|
| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | |
| MULTD | F0 | F2 | F4 | 6 | | | |
| SUBD | F8 | F6 | F2 | 7 | | | |
| DIVD | F10 | F0 | F6 | | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

| Time | Name | Busy | <i>Op</i> | <i>dest</i> | <i>S1</i> | <i>S2</i> | <i>FU</i> | <i>FU</i> | <i>Fj?</i> | <i>Fk?</i> |
|------|---------|------|-----------|-------------|-----------|-----------|-----------|-----------|------------|------------|
| | | | | <i>Fi</i> | <i>Fj</i> | <i>Fk</i> | <i>Qj</i> | <i>Qk</i> | <i>Rj</i> | <i>Rk</i> |
| | Integer | Yes | Load | F2 | | R3 | | | | Yes |
| | Mult1 | Yes | Mult | F0 | F2 | F4 | Integer | | No | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Sub | F8 | F6 | F2 | Integer | | Yes | No |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 7 | | | | | | | | | |
| | Mult1 | Integer | | | Add | | | | |

- Load execution completed in one clock cycle (data cache hit)
- Read multiply operands? *Not yet*
- SUBD can be issued to ADD Functional Unit (then SUBD has to wait for RAW F2 from load)

Scoreboard Example: Cycle 8

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> | |
|----------------------------|-----|----------|----------|--------------|-------------|--------------|---------------|
| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | |
| MULTD | F0 | F2 | F4 | 6 | | | |
| SUBD | F8 | F6 | F2 | 7 | | | |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|-------------|-------------|-------------|-----------|----------------|--------------|--------------|--------------|--------------|---------------|---------------|
| Integer | | Yes | Load | F2 | | R3 | | | | No |
| Mult1 | | Yes | Mult | F0 | F2 | F4 | Integer | | No | Yes |
| Mult2 | | No | | | | | | | | |
| Add | | Yes | Sub | F8 | F6 | F2 | | Integer | Yes | No |
| Divide | | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 8 | | | | | | | | | |
| <i>FU</i> | Mult1 | Integer | | | Add | Divide | | | |

- DIVD is issued but there is another RAW hazard (F0) from MULTD
-> DIVD has to wait for reading F0

Scoreboard Example: Cycle 8 cont'd

Instruction status:

| | | | | Read | Exec | Write |
|-------------|-----|----------|----------|-------|------|-------------|
| Instruction | | <i>j</i> | <i>k</i> | Issue | Oper | Comp Result |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 8 |
| MULTD | F0 | F2 | F4 | 6 | | |
| SUBD | F8 | F6 | F2 | 7 | | |
| DIVD | F10 | F0 | F6 | 8 | | |
| ADDD | F6 | F8 | F2 | | | |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|------|------------|----------|----------|----------|----------|-----------|-----------|
| | Integer | No | | | | | | | | |
| | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Sub | F8 | F6 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 8 | <i>FU</i> | Mult1 | | | | Add | Divide | | | |

- Load completes (Writes F2), and F2 operands for MULT and SUBD are ready

Scoreboard Example: Cycle 9

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Issue | Read <i>Oper</i> | Exec <i>Comp</i> | Write <i>Result</i> |
|-------------|----------|----------|-------|---------------------|---------------------|------------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | | |
| SUBD | F8 | F6 F2 | 7 | 9 | | |
| DIVD | F10 | F0 F6 | 8 | | | |
| ADDD | F6 | F8 F2 | | | | |

Functional unit status:

| Time | Name | Busy | Op | dest <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|------|-------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| 10 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 2 | Add | Yes | Sub | F8 | F6 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Note → Remaining

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|---------------------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 9 | FU Mult1 Add Divide | | | | | | | | |

- Read operands for MULTD & SUBD by multiple-port Register File (4 read ports)
- Issue ADDD? WAW F6 is gone but there is a structural hazard on ADD Functional Unit
- MULTD & SUBD are sent in execution in parallel with latency 10 cycles for MULTD & 2 cycles for SUBD

Scoreboard Example: Cycle 10

Instruction status:

| | | | | Read | Exec | Write |
|-------------|----------|----------|-------|------|------|--------|
| Instruction | <i>j</i> | <i>k</i> | Issue | Oper | Comp | Result |
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | | |
| SUBD | F8 | F6 F2 | 7 | 9 | | |
| DIVD | F10 | F0 F6 | 8 | | | |
| ADDD | F6 | F8 F2 | | | | |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|------|------------|----------|----------|----------|----------|-----------|-----------|
| | Integer | No | | | | | | | | |
| 9 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 1 | Add | Yes | Sub | F8 | F6 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|----|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 10 | FU | Mult1 | | | | Add | Divide | | | |

Scoreboard Example: Cycle 11

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Issue | Read <i>Oper</i> | Exec <i>Comp</i> | Write <i>Result</i> |
|-------------|----------|----------|-------|---------------------|---------------------|------------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | | |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | |
| DIVD | F10 | F0 F6 | 8 | | | |
| ADDD | F6 | F8 F2 | | | | |

Functional unit status:

| Time | Name | Busy | Op | dest <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|------|-------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| 8 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 0 | Add | Yes | Sub | F8 | F6 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 11 | Mult1 | | | | Add | Divide | | | |

- SUBD ends execution

Scoreboard Example: Cycle 12

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> | |
|----------------------------|----------|----------|--------------|-------------|-------------|---------------|----|
| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> | |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | | | | |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|------|------------|----------|----------|----------|----------|-----------|-----------|
| | Integer | No | | | | | | | | |
| 7 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> | |
|-------|-----------|------------------------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|--|
| 12 | <i>FU</i> | <div>Mult1Divide</div> | | | | | | | | | |

- SUBD writes result in F8

Scoreboard Example: Cycle 13

Instruction status:

| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|-----|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | 13 | | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|-------------|-------------|-------------|-----------|----------------|--------------|--------------|--------------|--------------|---------------|---------------|
| | Integer | No | | | | | | | | |
| 6 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 13 | <i>FU</i> | Mult1 | | | Add | | Divide | | | |

- ADDD can be issued (WAW F6 was gone and ADD unit is available)
- DIVD still waits for operand F0 from MULTD

Scoreboard Example: Cycle 14

Instruction status:

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> | |
|-------------|----------|----------|--------------|------------------|------------------|---------------------|----|
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | 13 | 14 | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|-------------|-------------|-------------|-----------|----------------|--------------|--------------|--------------|--------------|---------------|---------------|
| | Integer | No | | | | | | | | |
| 5 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 2 | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 14 | Mult1 | | | Add | | Divide | | | |

- ADDD reads operands (out-of-order read operands: ADDD reads operands before DIVD)

Scoreboard Example: Cycle 15

Instruction status:

| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|-----|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | 13 | 14 | | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|-------------|-------------|-------------|-----------|----------------|--------------|--------------|--------------|--------------|---------------|---------------|
| | Integer | No | | | | | | | | |
| 4 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 1 | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|----|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 15 | FU | Mult1 | | | Add | | Divide | | | |

- ADDD starts execution

Scoreboard Example: Cycle 16

Instruction status:

| <i>Instruction status:</i> | | | | <i>Read</i> | <i>Exec</i> | <i>Write</i> | |
|----------------------------|-----|----------|----------|--------------|-------------|--------------|---------------|
| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Oper</i> | <i>Comp</i> | <i>Result</i> |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | 13 | 14 | 16 | |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|------|------------|----------|----------|----------|----------|-----------|-----------|
| | Integer | No | | | | | | | | |
| 3 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| 0 | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|----|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 16 | FU | Mult1 | | | Add | | Divide | | | |

- ADDD ends execution, but WAR F6 must be detected before writing the result in RF

Scoreboard Example: Cycle 17

Instruction status:

| Instruction | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|-----|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | | |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | | | |
| ADDD | F6 | F8 | F2 | 13 | 14 | 16 | |

WAR F6 Hazard!

Functional unit status:

| Time | Name | Busy | Op | dest <i>Fi</i> | <i>S1 Fj</i> | <i>S2 Fk</i> | <i>FU Qj</i> | <i>FU Qk</i> | <i>Fj? Rj</i> | <i>Fk? Rk</i> |
|------|---------|------|------|-------------------|--------------|--------------|--------------|--------------|---------------|---------------|
| | Integer | No | | | | | | | | |
| 2 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 17 | <i>FU</i> | Mult1 | | | Add | | Divide | | | |

- Why not write result of ADDD??? WAR F6 must be detected before writing for result of ADDD in F6
- DIVD must first read F6 (before ADDD write F6), but DIVD cannot read operands until MULTD writes F0 (RAW on F0)

Scoreboard Example: Cycle 18

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | | |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | | | |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | |

Functional unit status:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>dest</i> <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|-------------|-------------|-------------|-----------|--------------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| 1 | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 18 | Mult1 | | | Add | | Divide | | | |

Scoreboard Example: Cycle 19

Instruction status:

| | | | | Read | Exec | Write |
|-------------|-----|----------|----------|-------|------|-------------|
| Instruction | | <i>j</i> | <i>k</i> | Issue | Oper | Comp Result |
| LD | F6 | 34+ | R2 | 1 | 2 | 3 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | 19 11 12 |
| SUBD | F8 | F6 | F2 | 7 | 9 | |
| DIVD | F10 | F0 | F6 | 8 | | |
| ADDD | F6 | F8 | F2 | 13 | 14 | 16 |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|------|------------|----------|----------|----------|----------|-----------|-----------|
| 0 | Integer | No | | | | | | | | |
| | Mult1 | Yes | Mult | F0 | F2 | F4 | | | Yes | Yes |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | Mult1 | | No | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 19 | <i>FU</i> | Mult1 | | | Add | | Divide | | | |

- MULTD ends execution

Scoreboard Example: Cycle 20

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Issue | Read <i>Oper</i> | Exec <i>Comp</i> | Write <i>Result</i> |
|-------------|----------|----------|-------|---------------------|---------------------|------------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | | | |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | |

Functional unit status:

| Time | Name | Busy | Op | dest <i>Fi</i> | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|-----|-------------------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | | | Yes | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 20 | Add | | | | | Divide | | | |

- MULTD writes in F0

Scoreboard Example: Cycle 21

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Read Exec Write | | | |
|-------------|----------|----------|-----------------|------|------|--------|
| | | | Issue | Oper | Comp | Result |
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | 21 | | |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | |

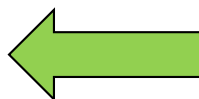
Functional unit status:

| Time | Name | Busy | Op | dest | | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|-----|-----------|-----------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | | | | <i>Fi</i> | <i>Fj</i> | | | | | | |
| | Integer | No | | | | | | | | | |
| | Mult1 | No | | | | | | | | | |
| | Mult2 | No | | | | | | | | | |
| | Add | Yes | Add | F6 | F8 | F2 | | | | Yes | Yes |
| | Divide | Yes | Div | F10 | F0 | F6 | | | | Yes | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 21 | | | | | | | | | |
| | | | | Add | | Divide | | | |

- DIVD can read operands
- WAR F6 hazard is now gone...



Scoreboard Example: Cycle 22

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | Read Exec Write | | | |
|-------------|----------|----------|-----------------|------|------|--------|
| | | | Issue | Oper | Comp | Result |
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | 21 | | |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | 22 |

Functional unit status:

| Time | Name | Busy | Op | dest | | <i>S1</i> <i>Fj</i> | <i>S2</i> <i>Fk</i> | <i>FU</i> <i>Qj</i> | <i>FU</i> <i>Qk</i> | <i>Fj?</i> <i>Rj</i> | <i>Fk?</i> <i>Rk</i> |
|------|---------|------|-----|-----------|-----------|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| | | | | <i>Fi</i> | <i>Fj</i> | | | | | | |
| | Integer | No | | | | | | | | | |
| | Mult1 | No | | | | | | | | | |
| | Mult2 | No | | | | | | | | | |
| | Add | No | | | | | | | | | |
| 39 | Divide | Yes | Div | F10 | F0 | F6 | | | | Yes | Yes |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 22 | | | | | | | | | |
| | FU Divide | | | | | | | | |

- DIVD has read its operands in previous cycle, so WAR F6 is gone
- ADDD can now write the result in F6



skipping some cycles...

Scoreboard Example: Cycle 61

Instruction status:

Instruction status:

| Instruction | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Read Oper</i> | <i>Exec Comp</i> | <i>Write Result</i> |
|-------------|----------|----------|--------------|------------------|------------------|---------------------|
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | 21 | 61 | |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | 22 |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest Fi | S1 Fj | S2 Fk | FU Qj | FU Qk | Fj? Rj | Fk? Rk |
|------|---------|------|-----|------------|----------|----------|----------|----------|-----------|-----------|
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| 0 | Divide | Yes | Div | F10 | F0 | F6 | | | Yes | Yes |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|----|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 61 | FU | Divide | | | | | | | | |

- DIVD ends execution

Scoreboard Example: Cycle 62

Instruction status:

instruction status:

| Instruction | <i>j</i> | <i>k</i> | Issue | Read Oper | Exec Comp | Write Result | |
|-------------|----------|----------|-------|-----------|-----------|--------------|----|
| LD | F6 | 34+ | R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ | R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 | F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 | F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 | F6 | 8 | 21 | 61 | 62 |
| ADDD | F6 | F8 | F2 | 13 | 14 | 16 | 22 |

Functional unit status:

l unit status:

| | | | | <i>dest</i> | <i>S1</i> | <i>S2</i> | <i>FU</i> | <i>FU</i> | <i>Fj?</i> | <i>Fk?</i> |
|-------------|-------------|-------------|-----------|-------------|-----------|-----------|-----------|-----------|------------|------------|
| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Fi</i> | <i>Fj</i> | <i>Fk</i> | <i>Qj</i> | <i>Qk</i> | <i>Rj</i> | <i>Rk</i> |
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 62 | <i>FU</i> | | | | | | | | | |

- DIVD writes in F10

Recap: Scoreboard Example: Cycle 62

Instruction status:

| | | | | Read | Exec | Write |
|-------------|----------|----------|-------|------|------|--------|
| Instruction | <i>j</i> | <i>k</i> | Issue | Oper | Comp | Result |
| LD | F6 | 34+ R2 | 1 | 2 | 3 | 4 |
| LD | F2 | 45+ R3 | 5 | 6 | 7 | 8 |
| MULTD | F0 | F2 F4 | 6 | 9 | 19 | 20 |
| SUBD | F8 | F6 F2 | 7 | 9 | 11 | 12 |
| DIVD | F10 | F0 F6 | 8 | 21 | 61 | 62 |
| ADDD | F6 | F8 F2 | 13 | 14 | 16 | 22 |

Functional unit status:

unit status:

| Time | Name | Busy | Op | dest | S1 | S2 | FU | FU | Fj? | Fk? |
|------|---------|------|----|------|----|----|----|----|-----|-----|
| | | | | Fi | Fj | Fk | Qj | Qk | Rj | Rk |
| | Integer | No | | | | | | | | |
| | Mult1 | No | | | | | | | | |
| | Mult2 | No | | | | | | | | |
| | Add | No | | | | | | | | |
| | Divide | No | | | | | | | | |

Register result status:

| Clock | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | ... | <i>F30</i> |
|-------|-----------|-----------|-----------|-----------|-----------|------------|------------|-----|------------|
| 62 | FU | | | | | | | | |

- *In-order issue*
- *Out-of-order reading operands & execute & commit*

Reference

Appendix A of the text book: J. Hennessey, D. Patterson,
“*Computer Architecture: a quantitative approach*”
4th Edition, Morgan-Kaufmann Publishers.