

OUT-OF-ORDER EXECUTION

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Overview

- Announcement

 - Homework 2 submission deadline: Oct. 3rd

- This lecture

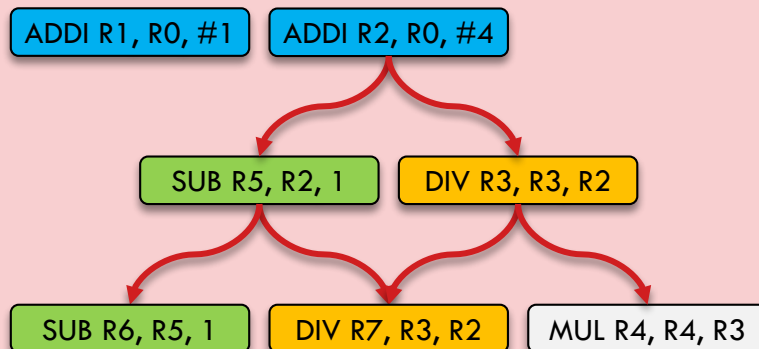
 - Tomasulo algorithm

 - Three-step OoO scheduling
 - Hardware implementation
 - Four-step algorithm
 - Reorder buffer

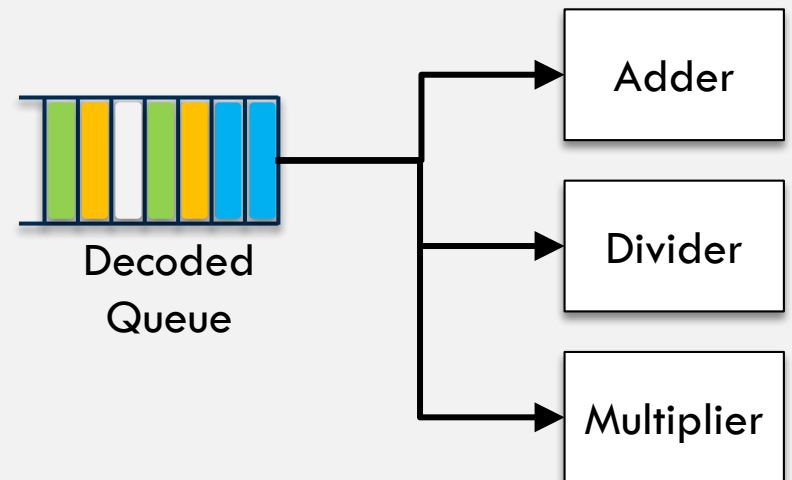
Recall: Dynamic Scheduling

- The main idea is to issue dynamic instructions out of program order while maintaining data flow

Program Data Flow



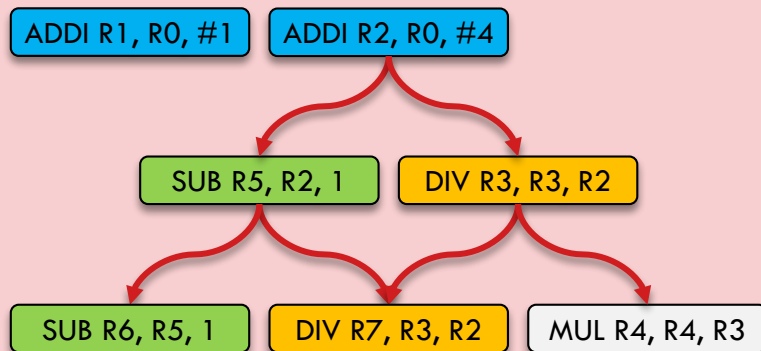
Functional Units



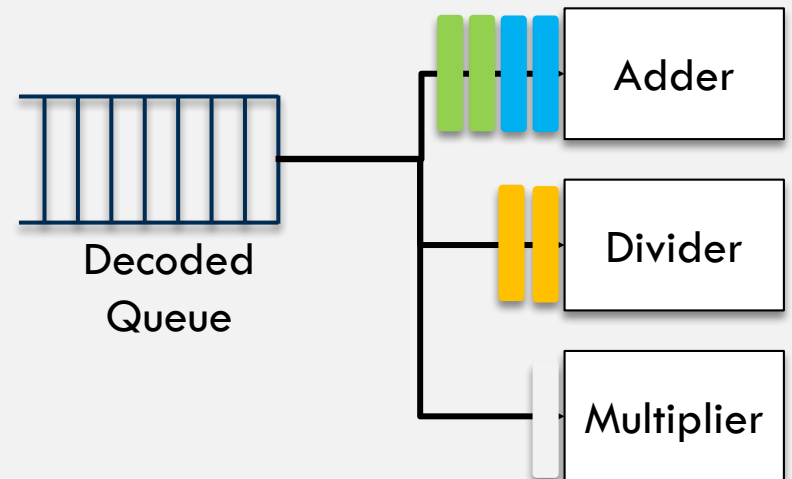
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- The main idea is to issue dynamic instructions out of program order while maintaining data flow

Program Data Flow



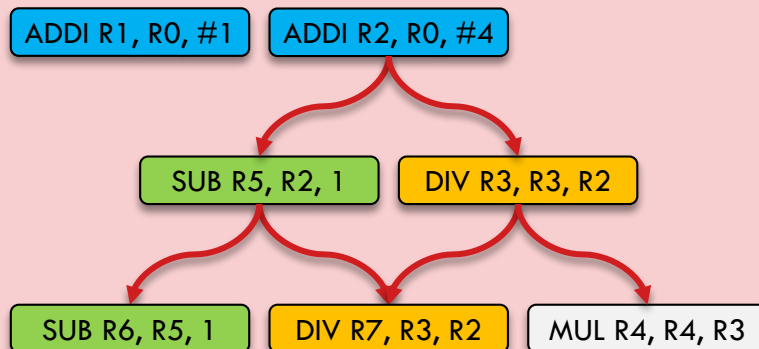
Functional Units



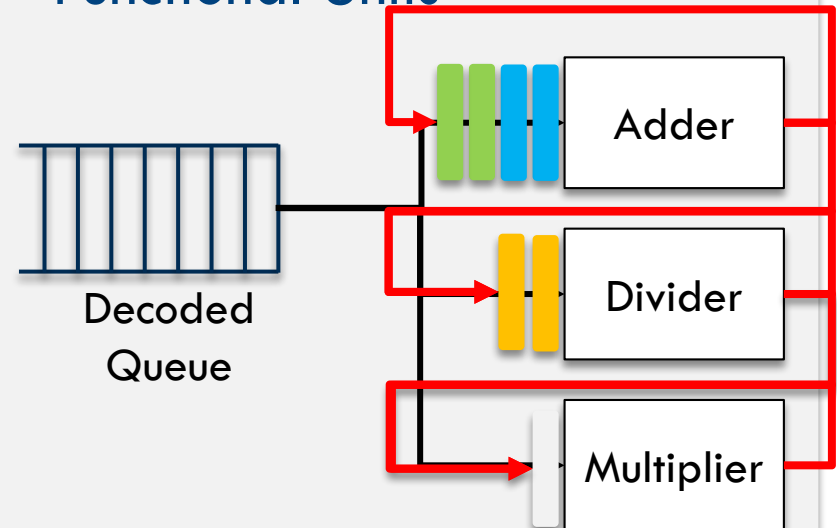
Recall: Dynamic Scheduling

- The main idea is to issue dynamic instructions out of program order while maintaining data flow

Program Data Flow

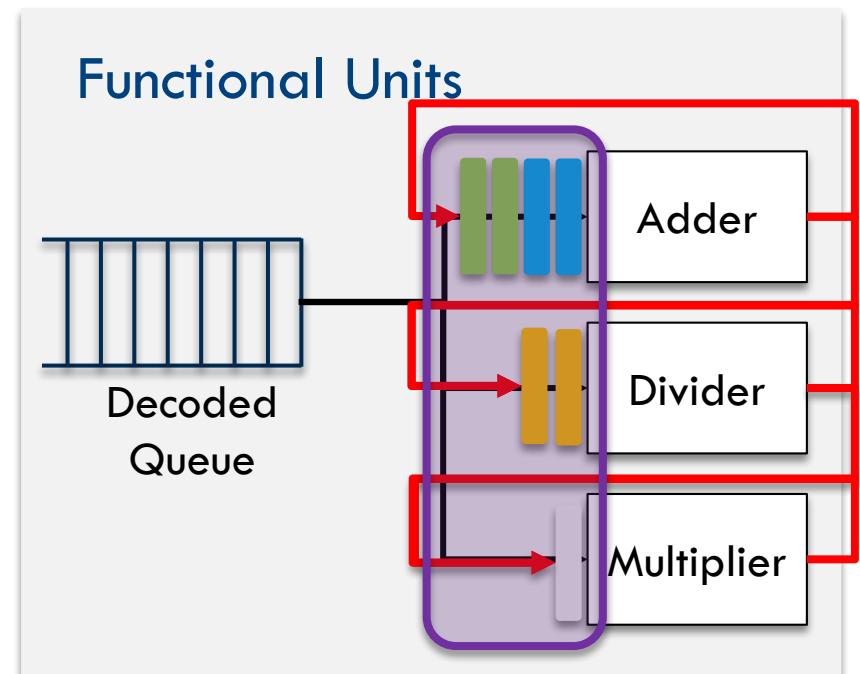
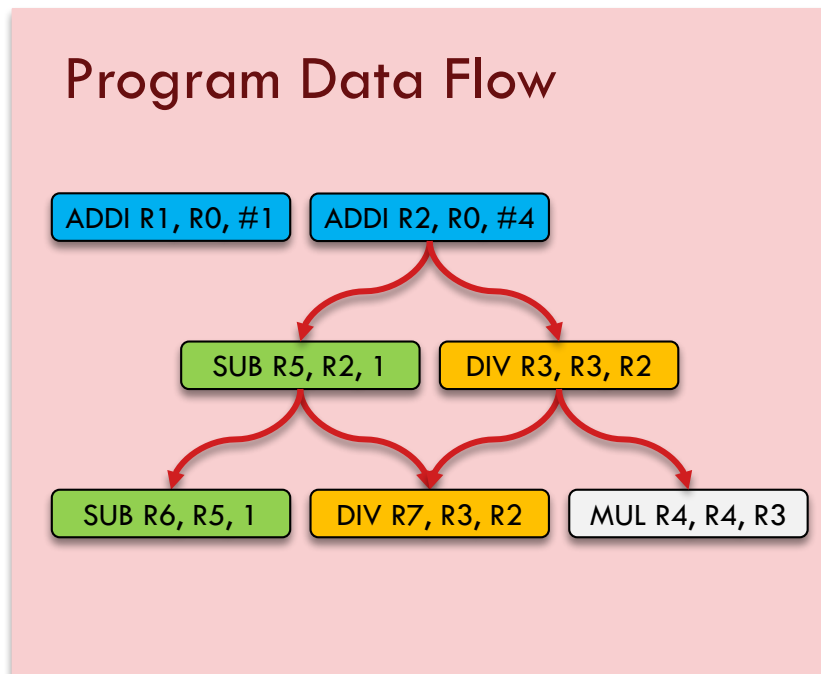


Functional Units



Recall: Dynamic Scheduling

- The main idea is to issue dynamic instructions out of program order while maintaining data flow



Reservation Stations

Tomasulo Algorithm

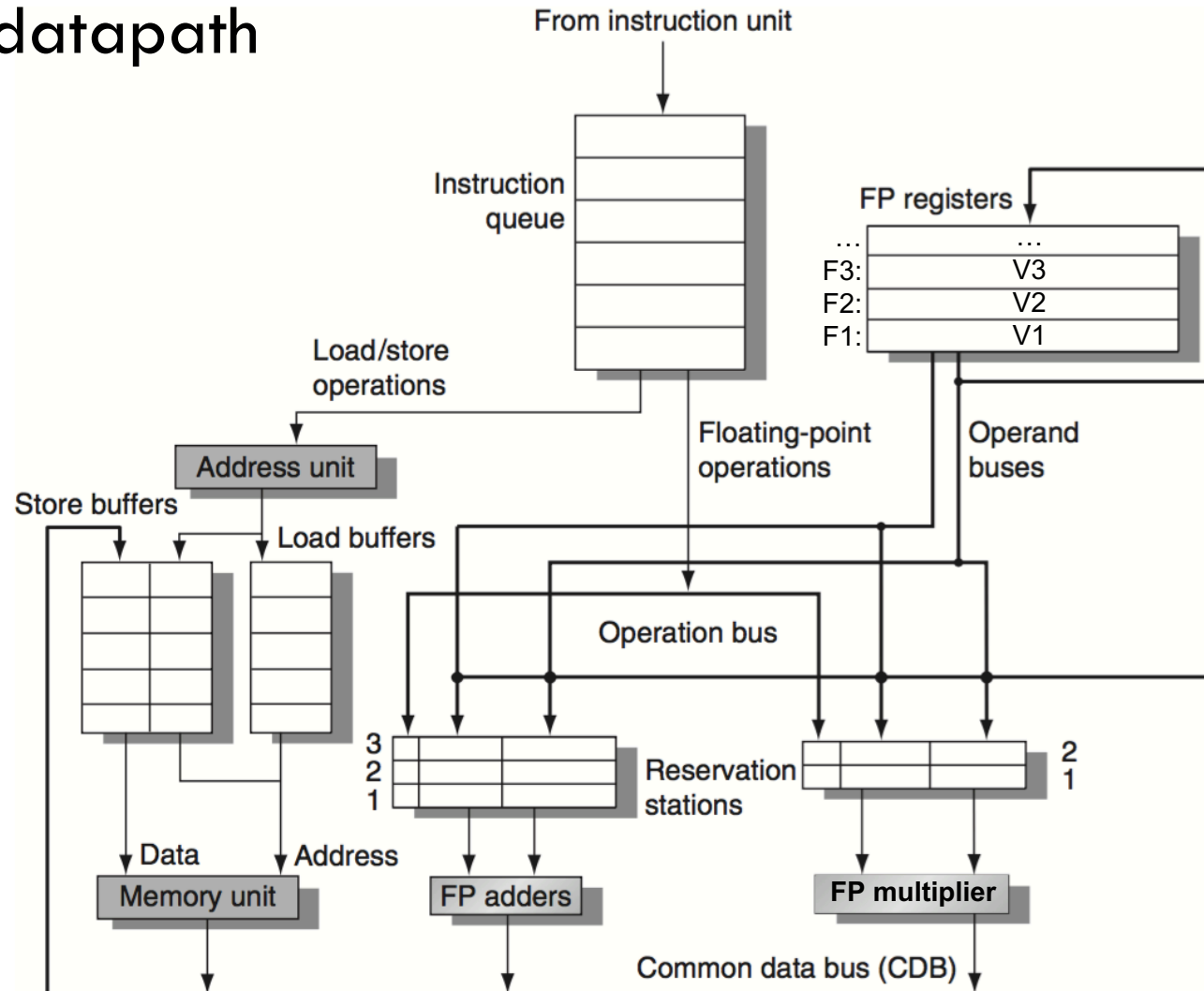
- Dispatch instructions to functional units
 - ▣ Use reservation stations (RS)
- Execute an instruction as soon as all of its operands are ready
 - ▣ Watch the common data bus (CDB)
- Remove false (anti- and output-) data dependence
 - ▣ Rename destination register to RS name

Three-Step Tomasulo Algorithm

- **Issue:** take an instruction from the instruction queue
 - ▣ If there are free reservation stations without structural hazards, rename and read/send operands or RS names
- **Execute:** operate on operand(s) when ready
 - ▣ If all of the operands are ready, execute; if not watch the common data bus
- **Write result:** update the register values
 - ▣ Write the result through CDB to all waiting reservation stations and the register file; release the RS entry

Hardware Implementation

□ Example FP datapath

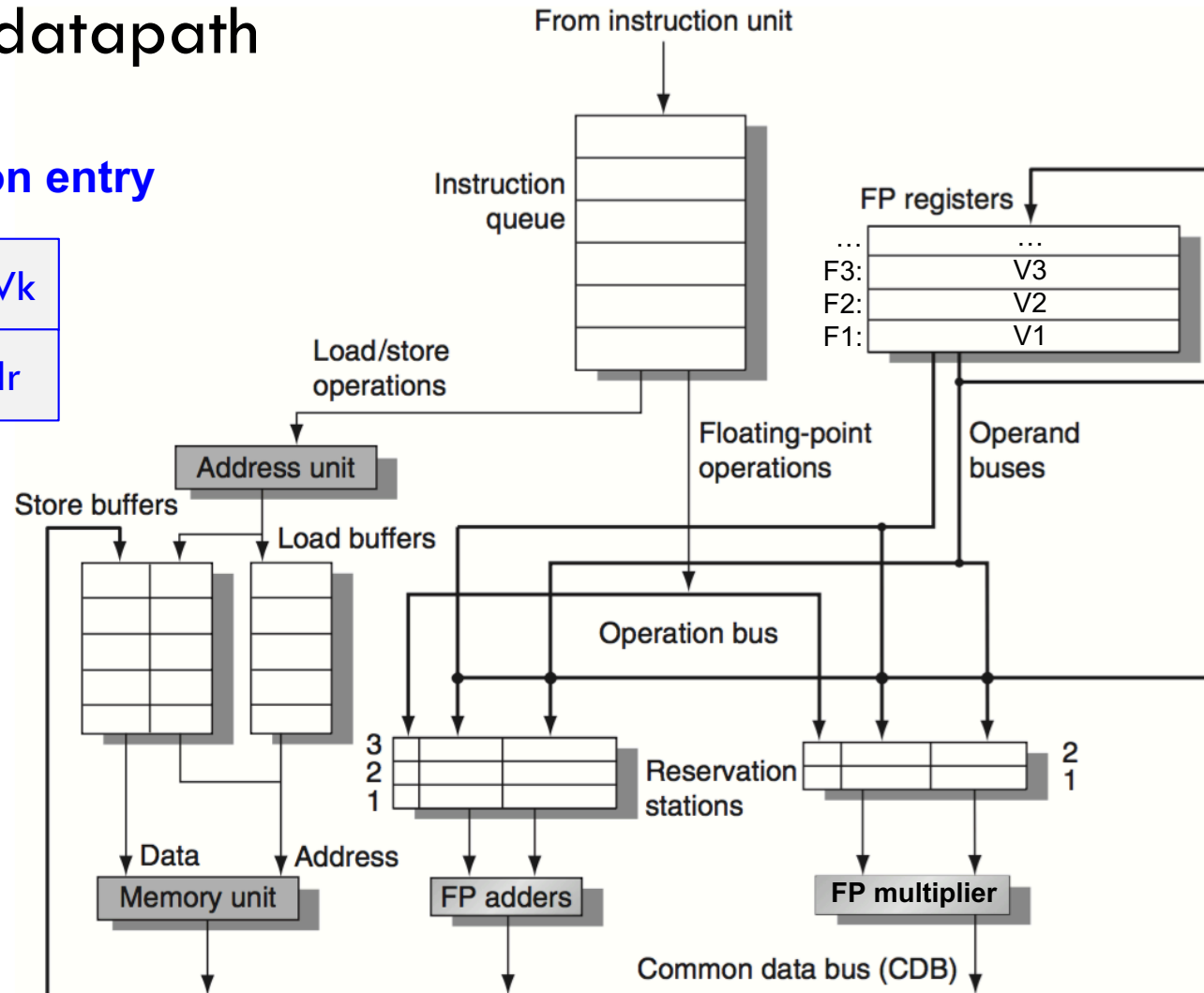


Hardware Implementation

□ Example FP datapath

Reservation station entry

| | | | |
|----------------|----------------|----------------|----------------|
| Busy | Op | V _j | V _k |
| Q _j | Q _k | Addr | |



Hardware Implementation

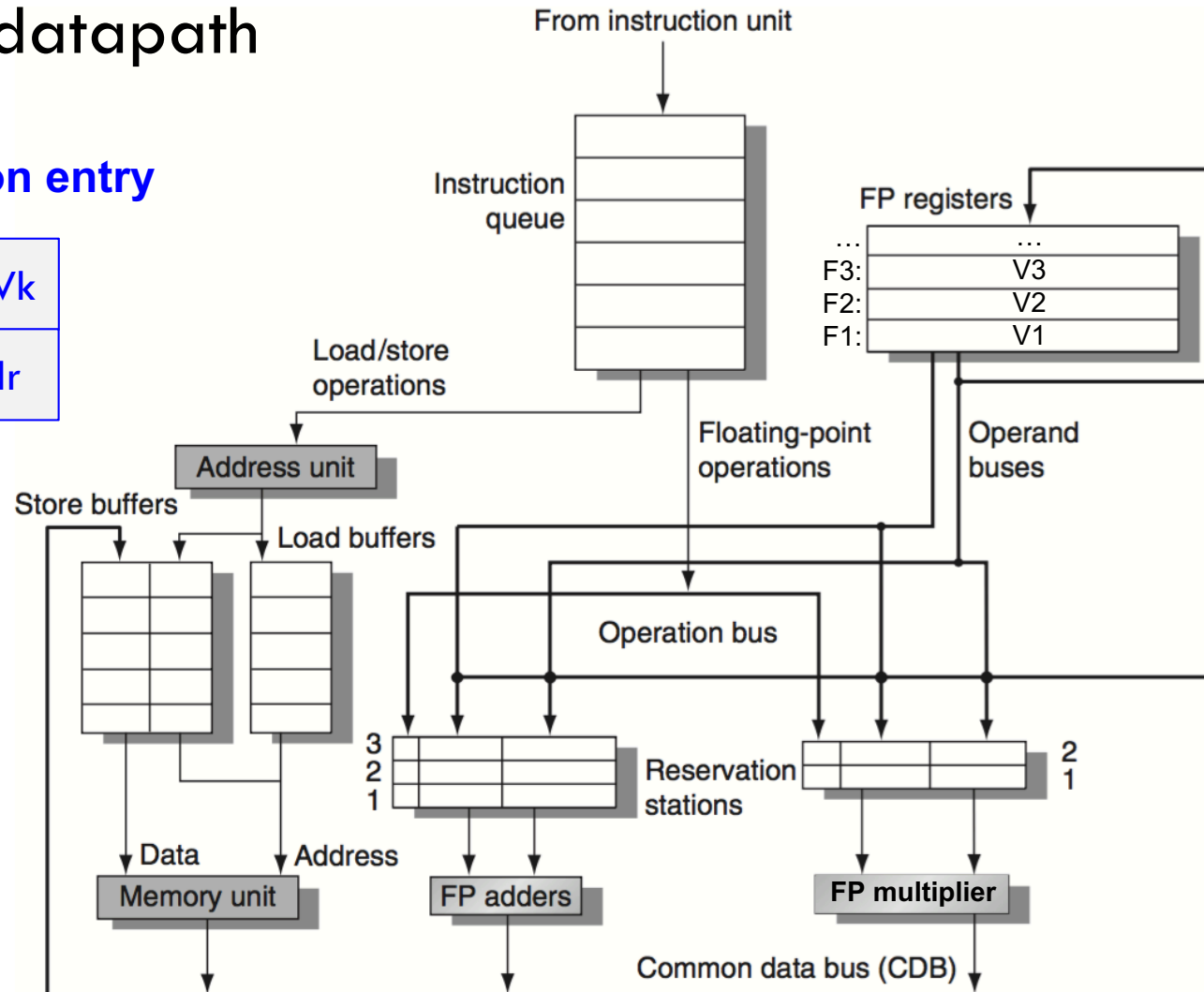
□ Example FP datapath

Reservation station entry

| | | | |
|------|----|------|----|
| Busy | Op | Vj | Vk |
| Qj | Qk | Addr | |

Code:

ADD F1, F2, F3
MUL F6, F1, F3



Hardware Implementation

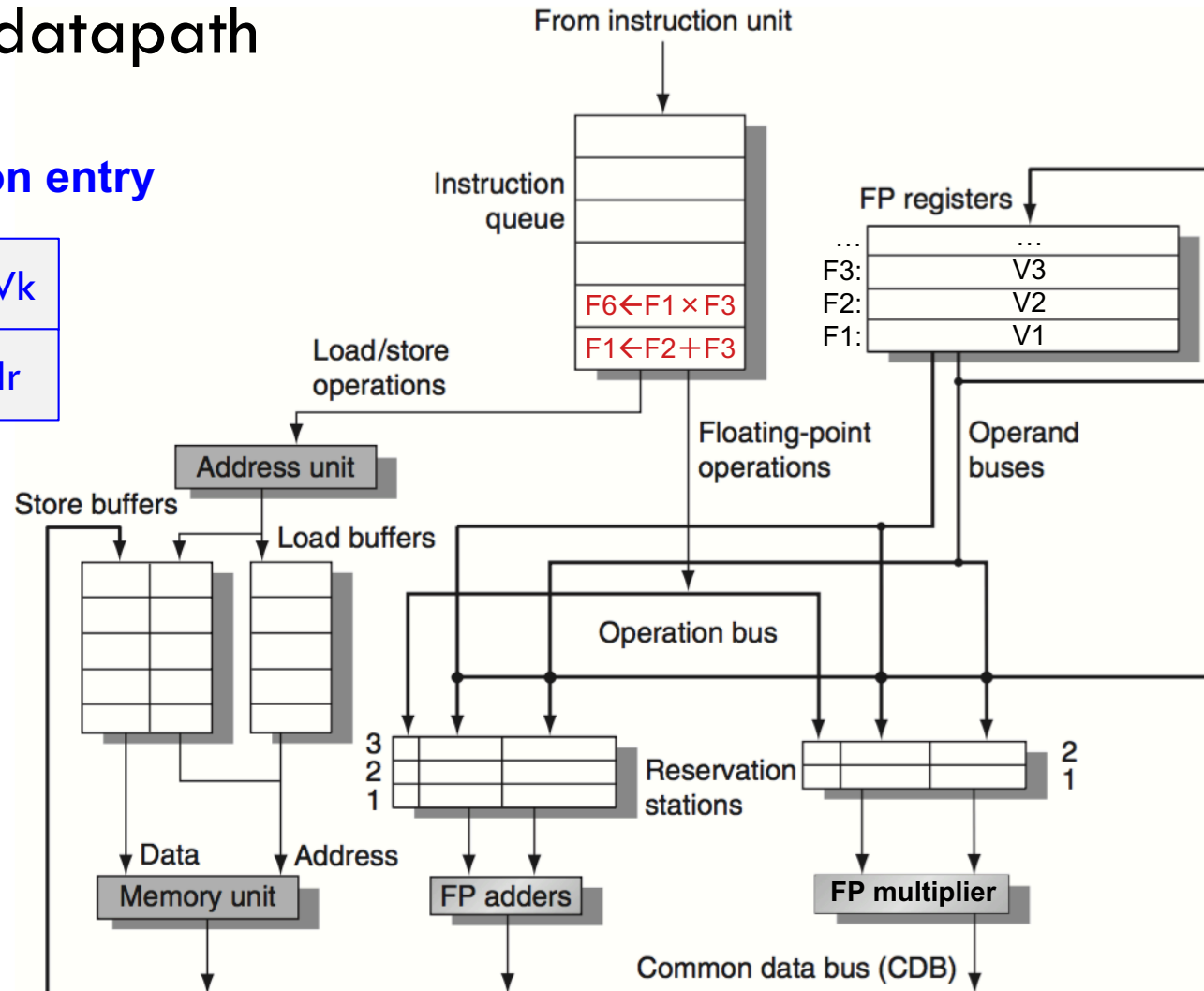
□ Example FP datapath

Reservation station entry

| | | | |
|------|----|------|----|
| Busy | Op | Vj | Vk |
| Qj | Qk | Addr | |

Code:

ADD F1, F2, F3
MUL F6, F1, F3



Hardware Implementation

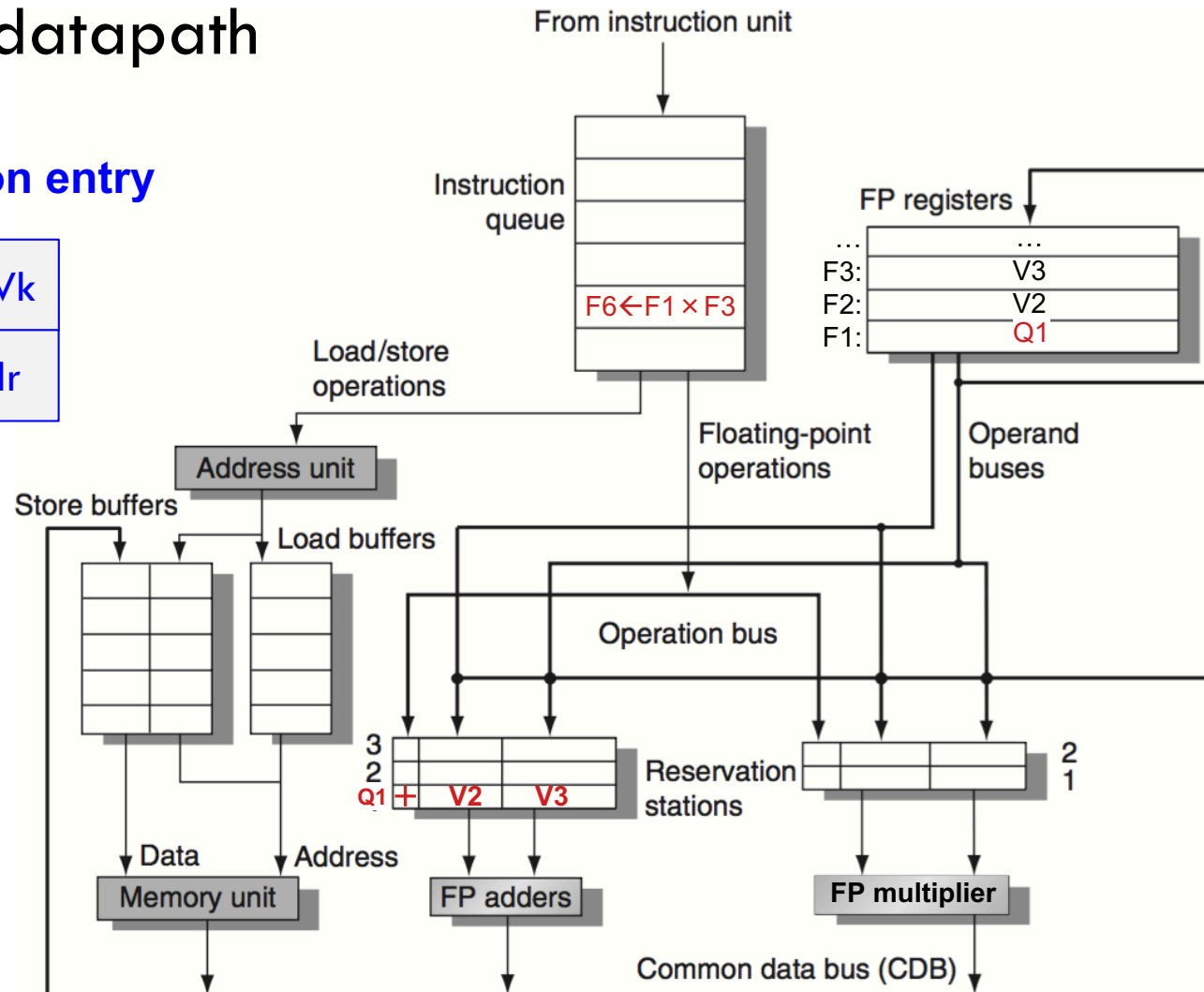
□ Example FP datapath

Reservation station entry

| | | | |
|------|----|------|----|
| Busy | Op | Vj | Vk |
| Qj | Qk | Addr | |

Code:

ADD F1, F2, F3
MUL F6, F1, F3



Hardware Implementation

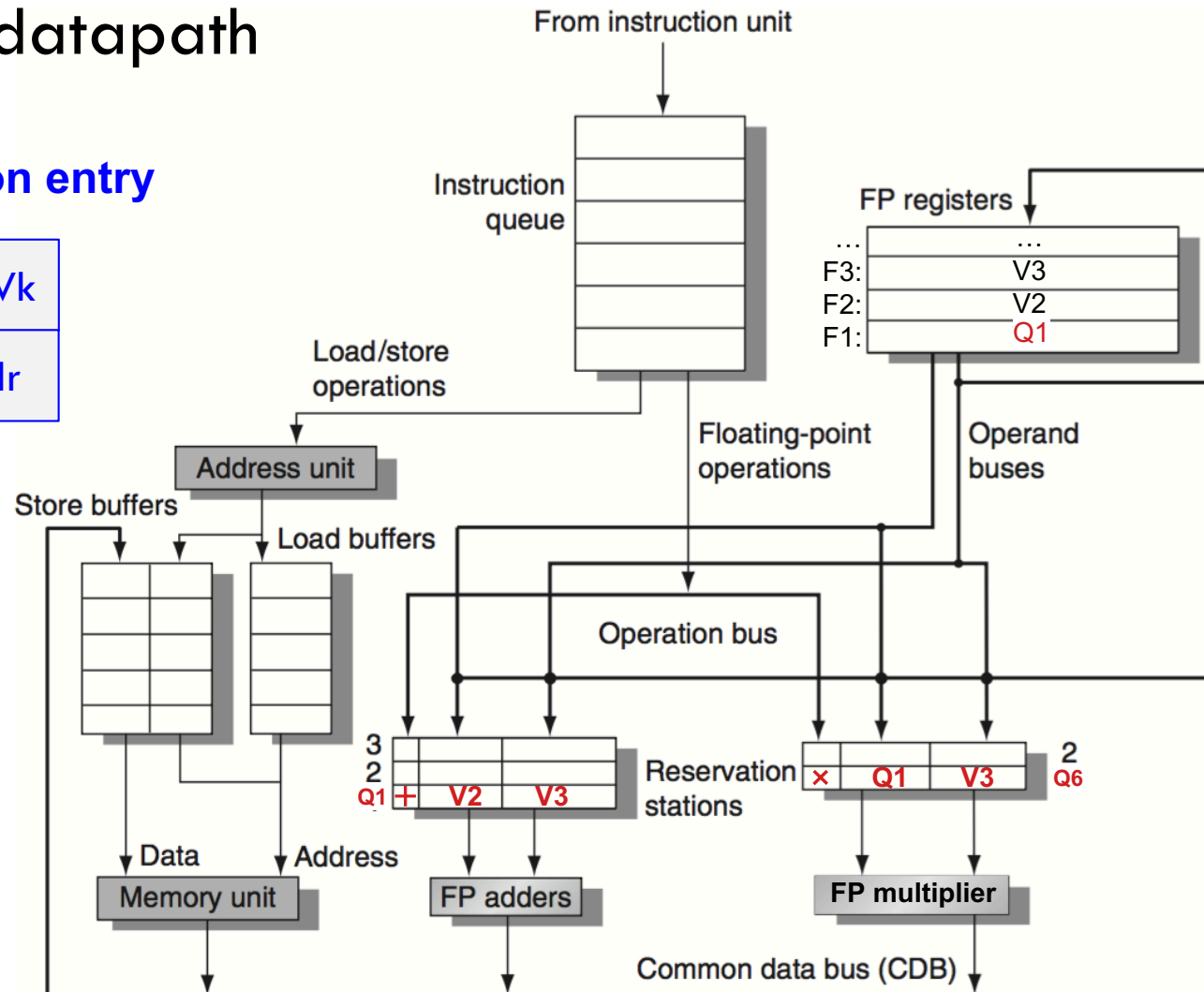
□ Example FP datapath

Reservation station entry

| | | | |
|------|----|------|----|
| Busy | Op | Vj | Vk |
| Qj | Qk | Addr | |

Code:

ADD F1, F2, F3
 MUL F6, F1, F3



Hardware Implementation

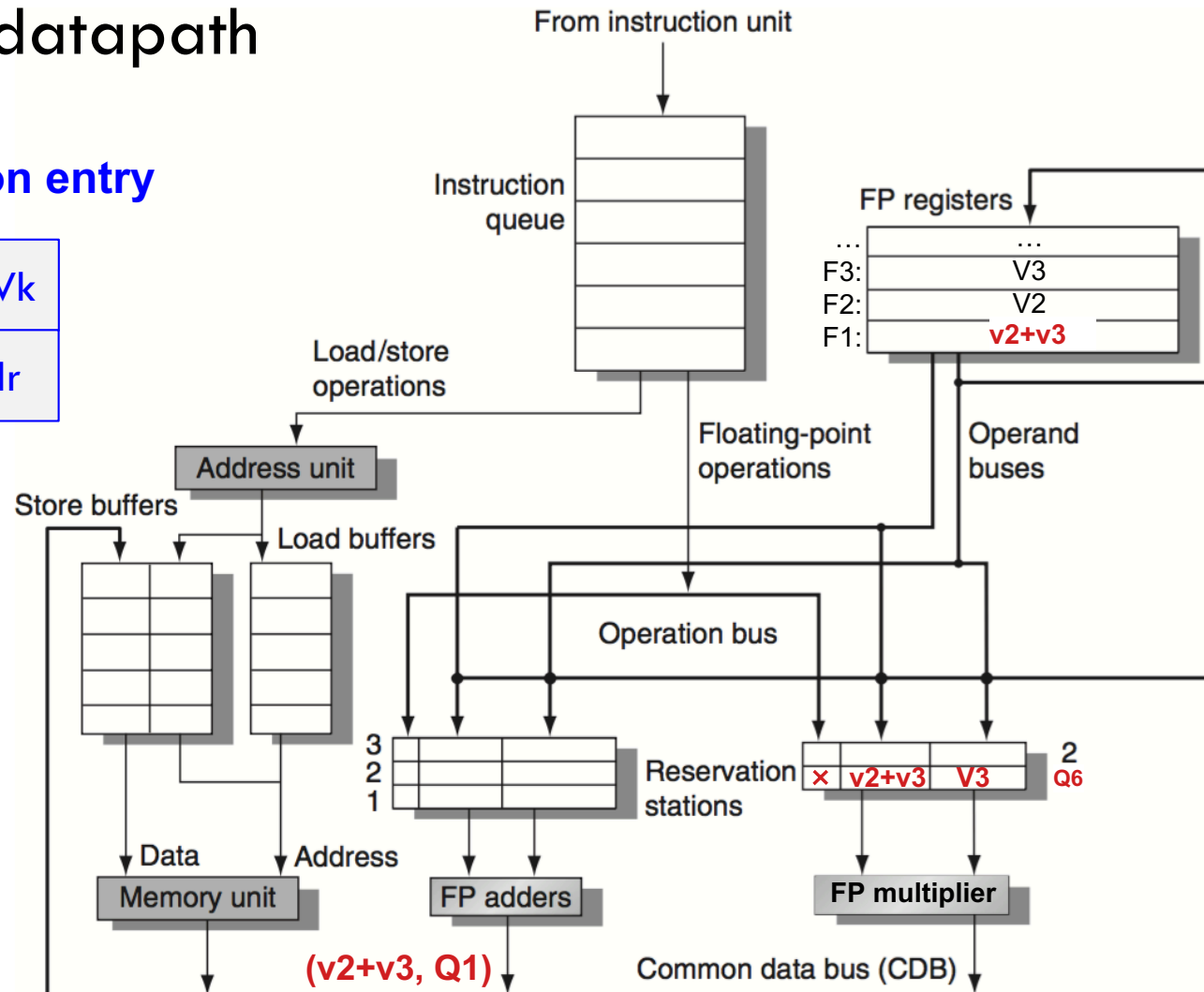
□ Example FP datapath

Reservation station entry

| | | | |
|------|----|------|----|
| Busy | Op | Vj | Vk |
| Qj | Qk | Addr | |

Code:

ADD F1, F2, F3
 MUL F6, F1, F3



Instruction Status

| Instruction | j | k | issue | complete | write |
|-------------|-----|--------|-------|----------|-------|
| LD | F6 | 43+ R2 | | | |
| LD | F2 | 45+ R3 | | | |
| MUL | F0 | F2 F4 | | | |
| SUB | F8 | F6 F2 | | | |
| DIV | F10 | F0 F6 | | | |
| ADD | F6 | F8 F2 | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|----|----|----|----|----|
| 2 | 0 | add1 | NO | | | | | |
| 2 | 0 | add2 | NO | | | | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 0 | mult1 | NO | | | | | |
| 40 | 0 | mult2 | NO | | | | | |

Register Result Status

[illegible]

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|-----------|------|
| LD | F6 | 43+ R2 | 1 | | | 2 | load1 | YES 43+R2 | 2 |
| LD | F2 | 45+ R3 | | | | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | | | | | | | |
| DIV | F10 | F0 F6 | | | | | | | |
| ADD | F6 | F8 F2 | | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|----|----|----|----|----|
| 2 | 0 | add1 | NO | | | | | |
| 2 | 0 | add2 | NO | | | | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 0 | mult1 | NO | | | | | |
| 40 | 0 | mult2 | NO | | | | | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 1 | value | value | value | load1 | value | value | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|-----------|------|
| LD | F6 | 43+ R2 | 1 | | | 2 | load1 | YES 43+R2 | 1 |
| LD | F2 | 45+ R3 | 2 | | | 2 | load2 | YES 45+R3 | 2 |
| MUL | F0 | F2 F4 | | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | | | | | | | |
| DIV | F10 | F0 F6 | | | | | | | |
| ADD | F6 | F8 F2 | | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|----|----|----|----|----|
| 2 | 0 | add1 | NO | | | | | |
| 2 | 0 | add2 | NO | | | | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 0 | mult1 | NO | | | | | |
| 40 | 0 | mult2 | NO | | | | | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|----------------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 2 | value | load2 | value | load1 | value | value | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|-----------|------|
| LD | F6 | 43+ R2 | 1 | 3 | | 2 | load1 | YES 43+R2 | 0 |
| LD | F2 | 45+ R3 | 2 | | | 2 | load2 | YES 45+R3 | 1 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | | | | | | | |
| DIV | F10 | F0 F6 | | | | | | | |
| ADD | F6 | F8 F2 | | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|------|----|-------|-------|----|
| 2 | 0 | add1 | NO | | | | | |
| 2 | 0 | add2 | NO | | | | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 0 | mult1 | YES | MULT | | value | load2 | |
| 40 | 0 | mult2 | NO | | | | | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 3 | | | | | | | | | |
| FU | mult1 | load2 | value | load1 | value | value | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|-----------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | | 2 | load2 | YES 45+R3 | 0 |
| MUL | F0 | F2 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 | 4 | | | | | | |
| DIV | F10 | F0 | | | | | | | |
| ADD | F6 | F8 | | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|------|-------|-------|-------|-------|
| 2 | 0 | add1 | YES | SUB | value | | | load2 |
| 2 | 0 | add2 | NO | | | | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 0 | mult1 | YES | MULT | | value | load2 | |
| 40 | 0 | mult2 | NO | | | | | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|-------|------|-------|-------|-----|-----|
| Clock 4 | | | | | | | | | |
| FU | mult1 | load2 | value | value | add1 | value | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | | | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | | | | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|-------|------|------|-------|-------|-------|----|
| 2 | add1 | YES | SUB | value | value | | |
| 2 | add2 | NO | | | | | |
| 2 | add3 | NO | | | | | |
| 10 | mult1 | YES | MULT | value | value | | |
| 40 | mult2 | YES | DIV | | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|-------|------|-------|-------|-----|-----|
| Clock 5 | mult1 | value | value | value | add1 | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | | | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|------|-------|-------|-------|----|
| 2 | 1 | add1 | YES | SUB | value | value | | |
| 2 | 0 | add2 | YES | ADD | | value | add1 | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 9 | mult1 | YES | MULT | value | value | | |
| 40 | 0 | mult2 | YES | DIV | | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|------|------|-------|-------|-----|-----|
| Clock 6 | mult1 | value | value | add2 | add1 | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|------|-------|-------|-------|----|
| 2 | 0 | add1 | YES | SUB | value | value | | |
| 2 | 0 | add2 | YES | ADD | | value | add1 | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 8 | mult1 | YES | MULT | value | value | | |
| 40 | 0 | mult2 | YES | DIV | | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|------|------|-------|-------|-----|-----|
| Clock 7 | mult1 | value | value | add2 | add1 | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | | | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|------|-------|-------|-------|
| 2 | 0 | add1 | NO | | | | |
| 2 | 2 | add2 | YES | ADD | value | value | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 7 | mult1 | YES | MULT | value | value | |
| 40 | 0 | mult2 | YES | DIV | | value | mult1 |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|------|-------|-------|-------|-----|-----|
| Clock 8 | mult1 | value | value | add2 | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | | | | | | |

Reservation Stations

| | Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|----|------|-------|------|------|-------|-------|-------|----|
| 2 | 0 | add1 | NO | | | | | |
| 2 | 1 | add2 | YES | ADD | value | value | | |
| 2 | 0 | add3 | NO | | | | | |
| 10 | 6 | mult1 | YES | MULT | value | value | | |
| 40 | 0 | mult2 | YES | DIV | | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|---------|-------|-------|-------|------|-------|-------|-------|-----|-----|
| Clock 9 | mult1 | value | value | add2 | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | 10 | | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|------|-------|-------|-------|
| 2 | 0 | add1 | NO | | | | |
| 2 | 0 | add2 | YES | ADD | value | value | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 5 | mult1 | YES | MULT | value | value | |
| 40 | 0 | mult2 | YES | DIV | | value | mult1 |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|----------|-------|-------|-------|------|-------|-------|-------|-----|-----|
| Clock 10 | mult1 | value | value | add2 | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | 10 | 11 | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|------|-------|-------|----|
| 2 | 0 | add1 | NO | | | | |
| 2 | 0 | add2 | NO | | | | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 4 | mult1 | YES | MULT | value | value | |
| 40 | 0 | mult2 | YES | DIV | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|----------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 11 | mult1 | value | value | value | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | 15 | | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | 10 | 11 | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|------|-------|-------|----|
| 2 | 0 | add1 | NO | | | | |
| 2 | 0 | add2 | NO | | | | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 0 | mult1 | YES | MULT | value | value | |
| 40 | 0 | mult2 | YES | DIV | value | mult1 | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|----------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 15 | mult1 | value | value | value | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | 15 | 16 | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | | | | | | |
| ADD | F6 | F8 F2 | 6 | 10 | 11 | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|-----|-------|-------|----|
| 2 | 0 | add1 | NO | | | | |
| 2 | 0 | add2 | NO | | | | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 0 | mult1 | NO | | | | |
| 40 | 40 | mult2 | YES | DIV | value | value | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 16 | value | value | value | value | value | mult2 | value | | |

Example: Out-of-order Execution

Instruction Status

| Instruction | j | k | issue | complete | write | | Busy | Address | Time |
|-------------|-----|--------|-------|----------|-------|---|-------|---------|------|
| LD | F6 | 43+ R2 | 1 | 3 | 4 | 2 | load1 | NO | 0 |
| LD | F2 | 45+ R3 | 2 | 4 | 5 | 2 | load2 | NO | 0 |
| MUL | F0 | F2 F4 | 3 | 15 | 16 | 2 | load3 | NO | 0 |
| SUB | F8 | F6 F2 | 4 | 7 | 8 | | | | |
| DIV | F10 | F0 F6 | 5 | 56 | | | | | |
| ADD | F6 | F8 F2 | 6 | 10 | 11 | | | | |

Reservation Stations

| Time | Name | Busy | Op | Vj | Vk | Qj | Qk |
|------|------|-------|-----|-----|-------|-------|----|
| 2 | 0 | add1 | NO | | | | |
| 2 | 0 | add2 | NO | | | | |
| 2 | 0 | add3 | NO | | | | |
| 10 | 0 | mult1 | NO | | | | |
| 40 | 0 | mult2 | YES | DIV | value | value | |

Register Result Status

| | F0 | F2 | F4 | F6 | F8 | F10 | F12 | ... | F30 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-----|-----|
| Clock 56 | value | value | value | value | value | mult2 | value | | |

Instruction Status

Summary of Tomasulo Algorithm

- Data hazards
- Structural hazards
- Precise exception handling

Summary of Tomasulo Algorithm

- Data hazards
 - ▣ RAW is handled by forwarding over CDB
 - ▣ WAR and WAW are removed by RS-based renaming
- Structural hazards
 - ▣ Multiple FUs may be accessing CDB simultaneously
- Precise exception handling
 - ▣ Not possible because of OoO writeback to register file

Summary of Tomasulo Algorithm

- Data hazards
 - ▣ RAW is handled by forwarding over CDB
 - ▣ WAR and WAW are removed by RS-based renaming
- Structural hazards
 - ▣ Multiple FUs may be accessing CDB simultaneously
 - Solution: delay conflicting instructions at issue and RS
- Precise exception handling
 - ▣ Not possible because of OoO writeback to register file
 - Solution: maintain the destination value in ROB (IW)

Four-Step Tomasulo Algorithm

- Issue (dispatch)
 - ▣ If RS and ROB slots are free; read/rename operands
- Execution
 - ▣ Execute operation as soon as the operand values are ready
- Write result
 - ▣ Send result to ROB and reservation stations via CDB
- Commit (retire)
 - ▣ Update register file for the head of ROB

Four-Step Tomasulo Algorithm

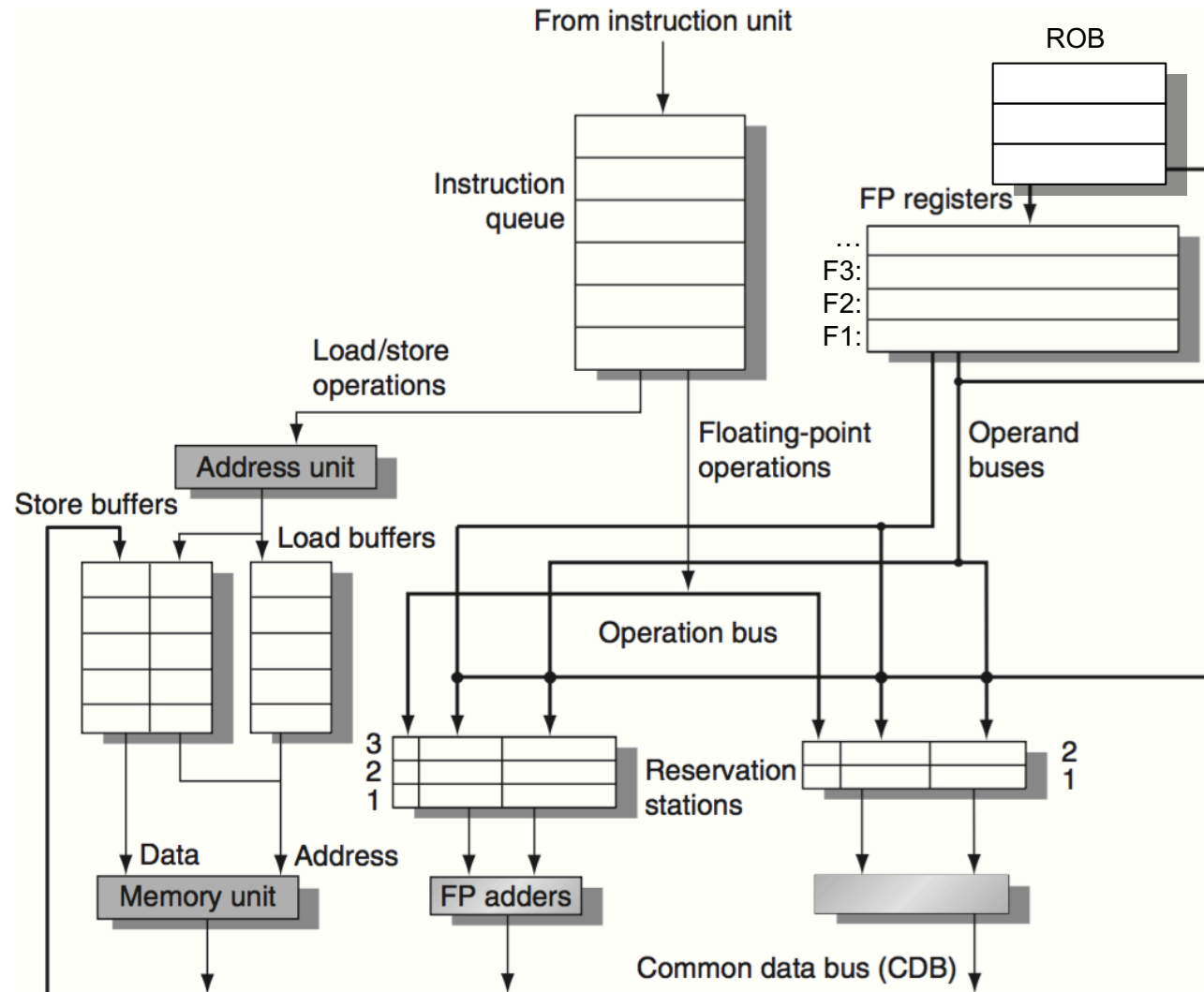
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

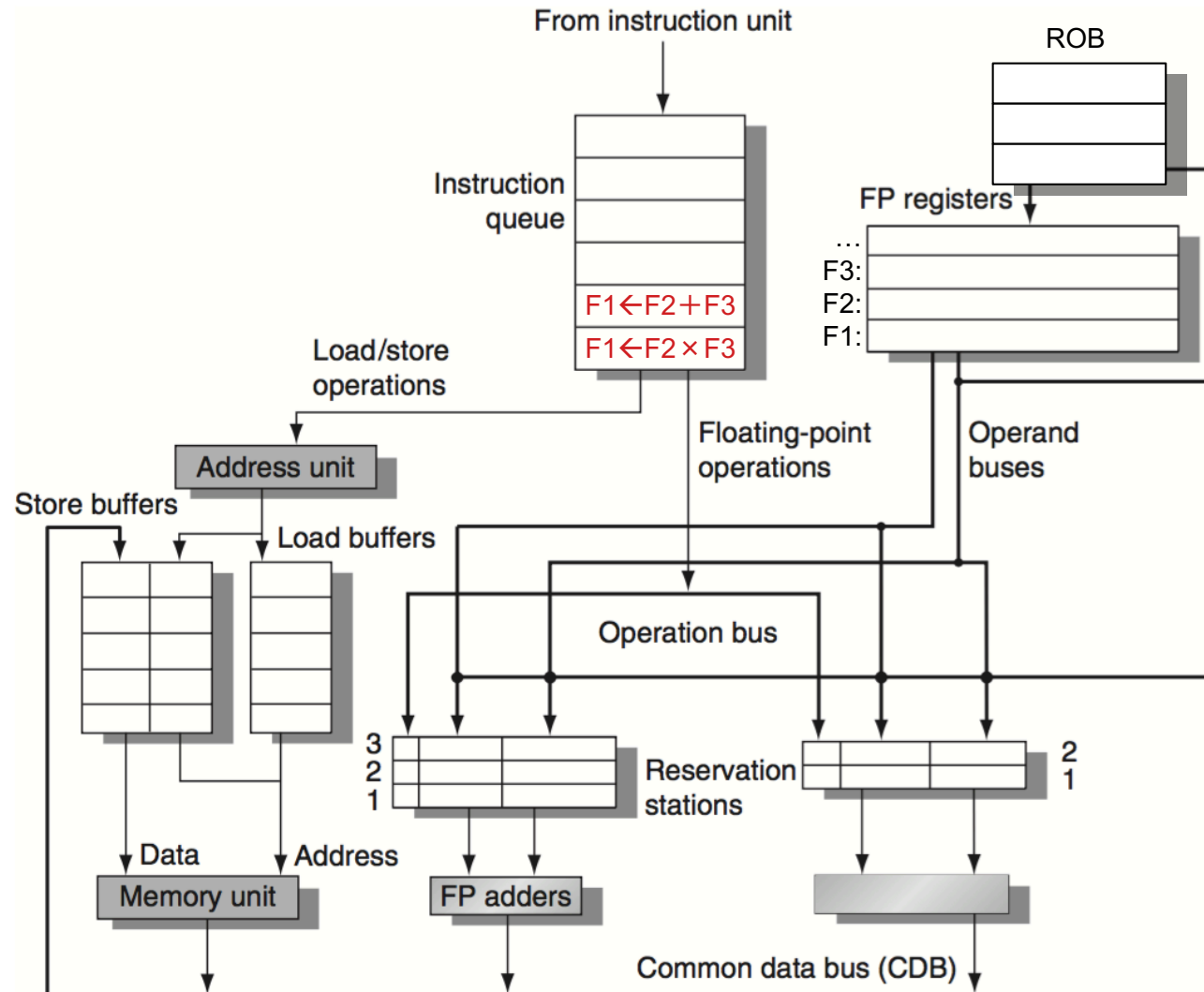
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

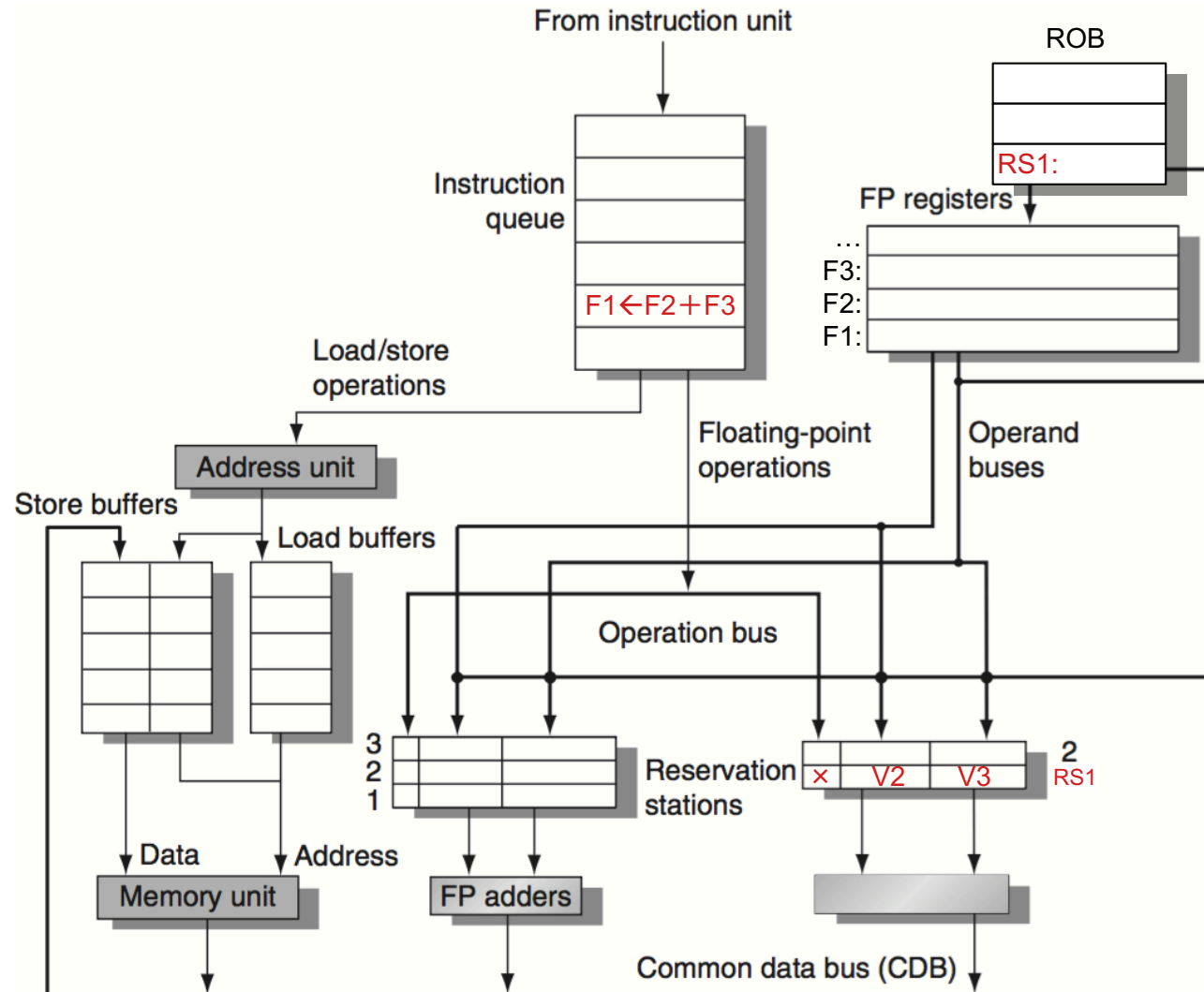
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

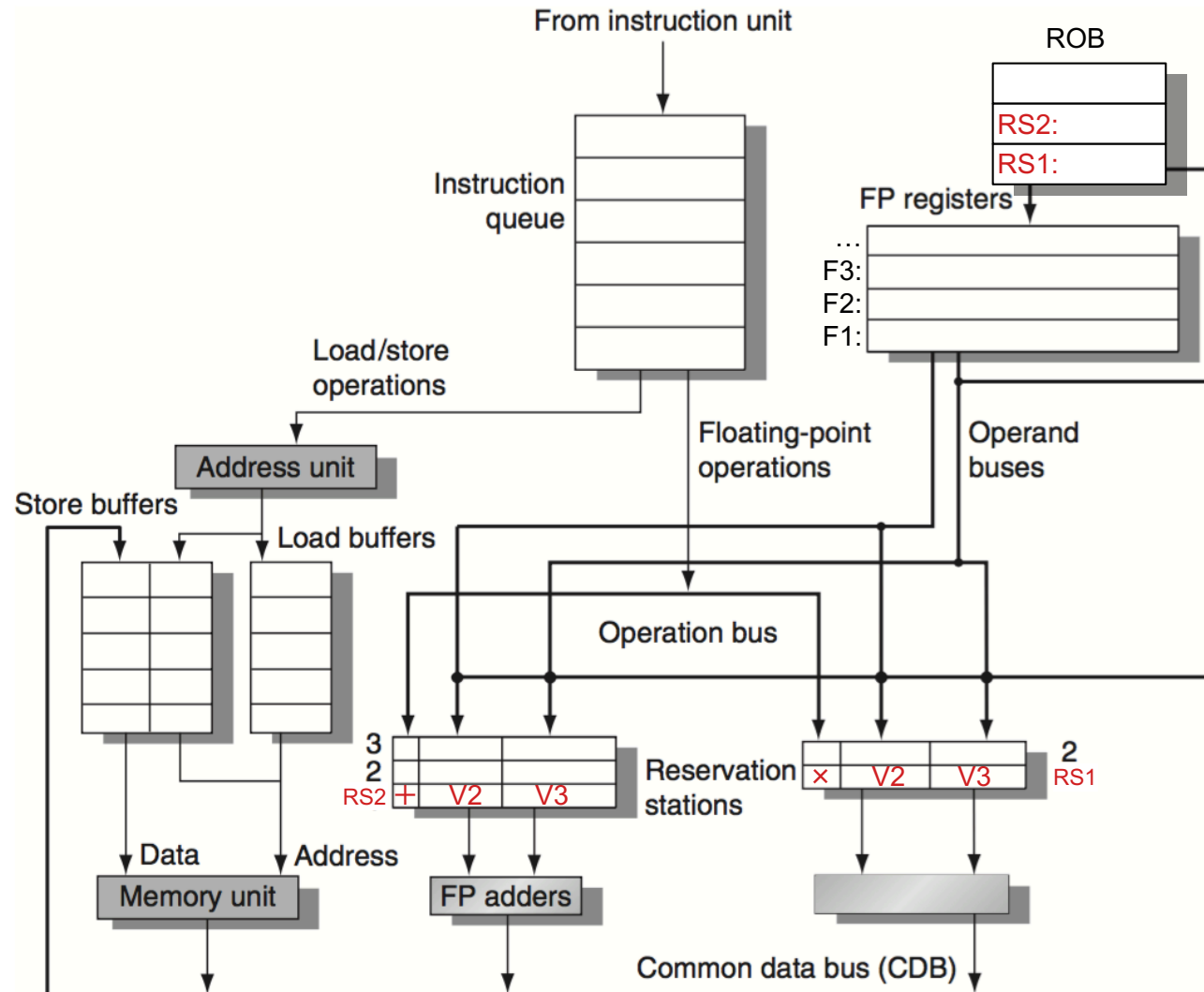
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

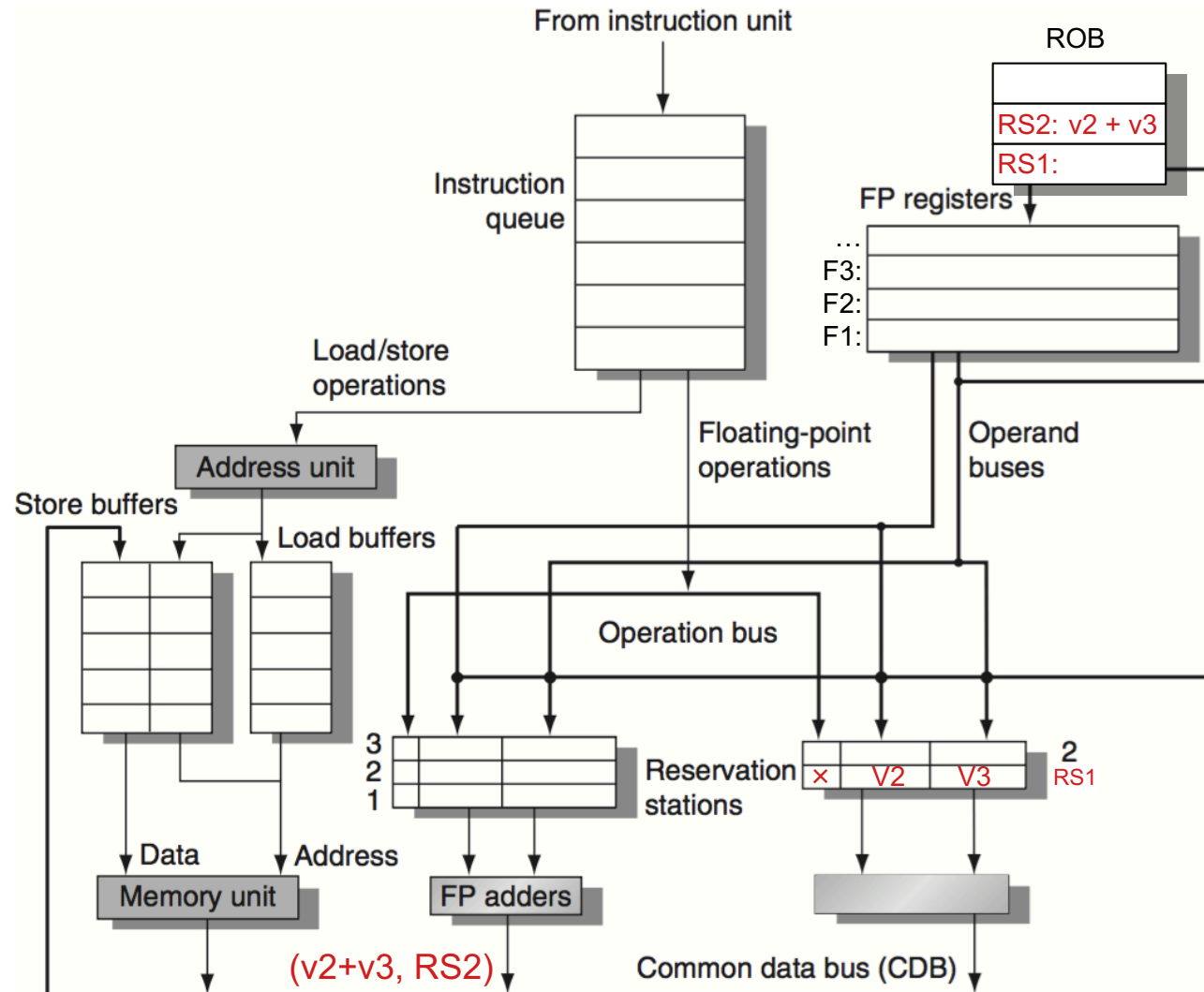
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

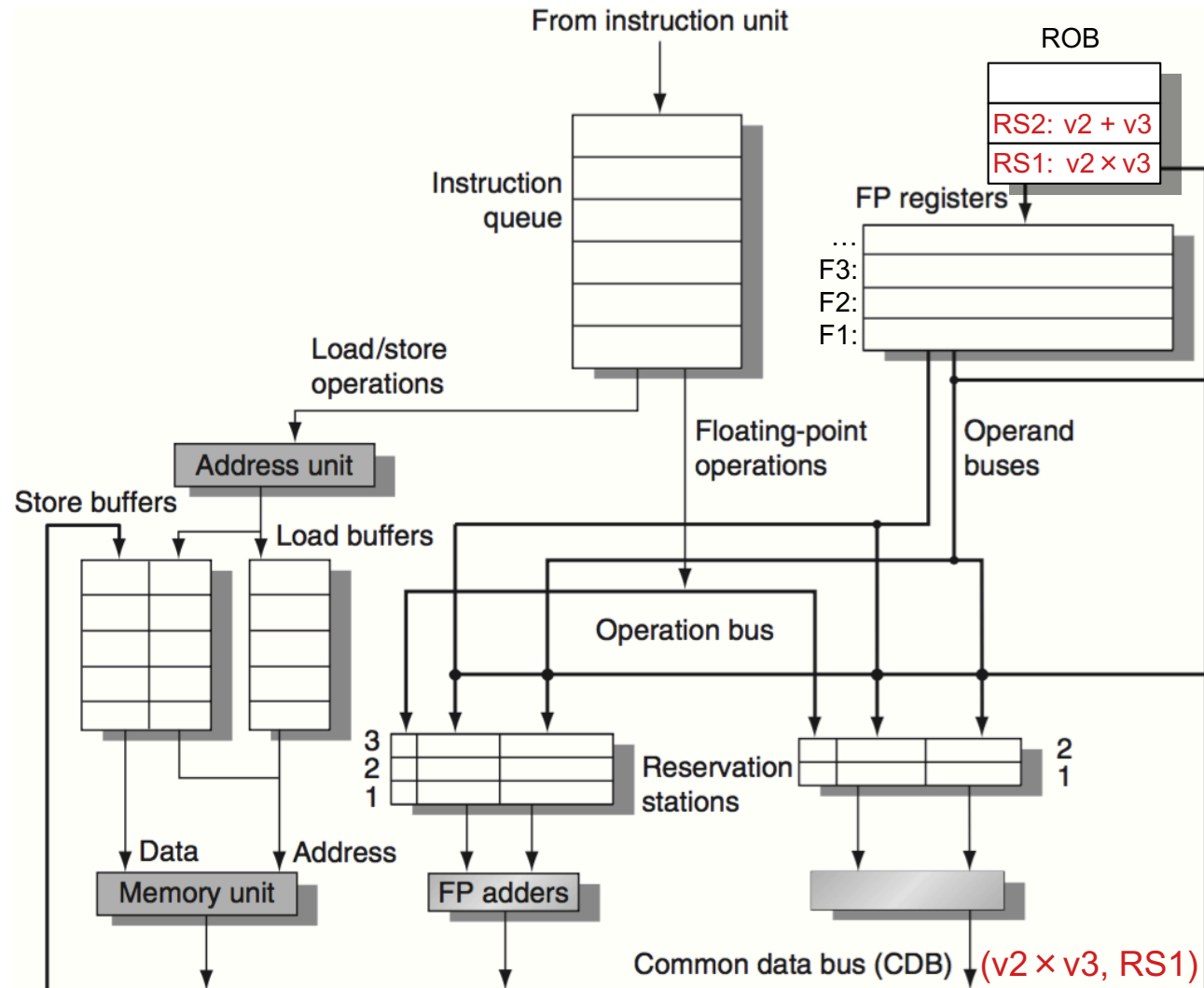
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

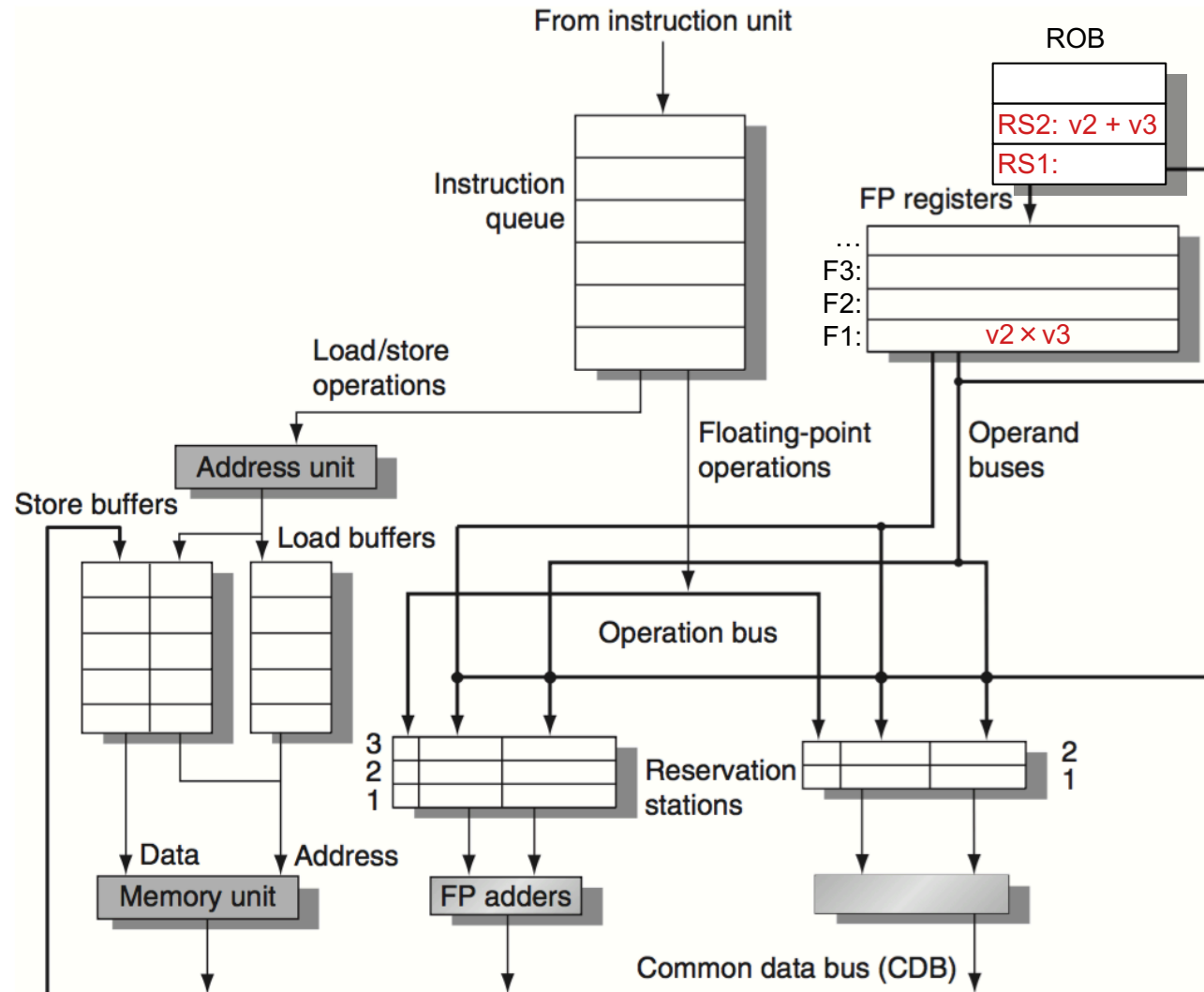
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



Four-Step Tomasulo Algorithm

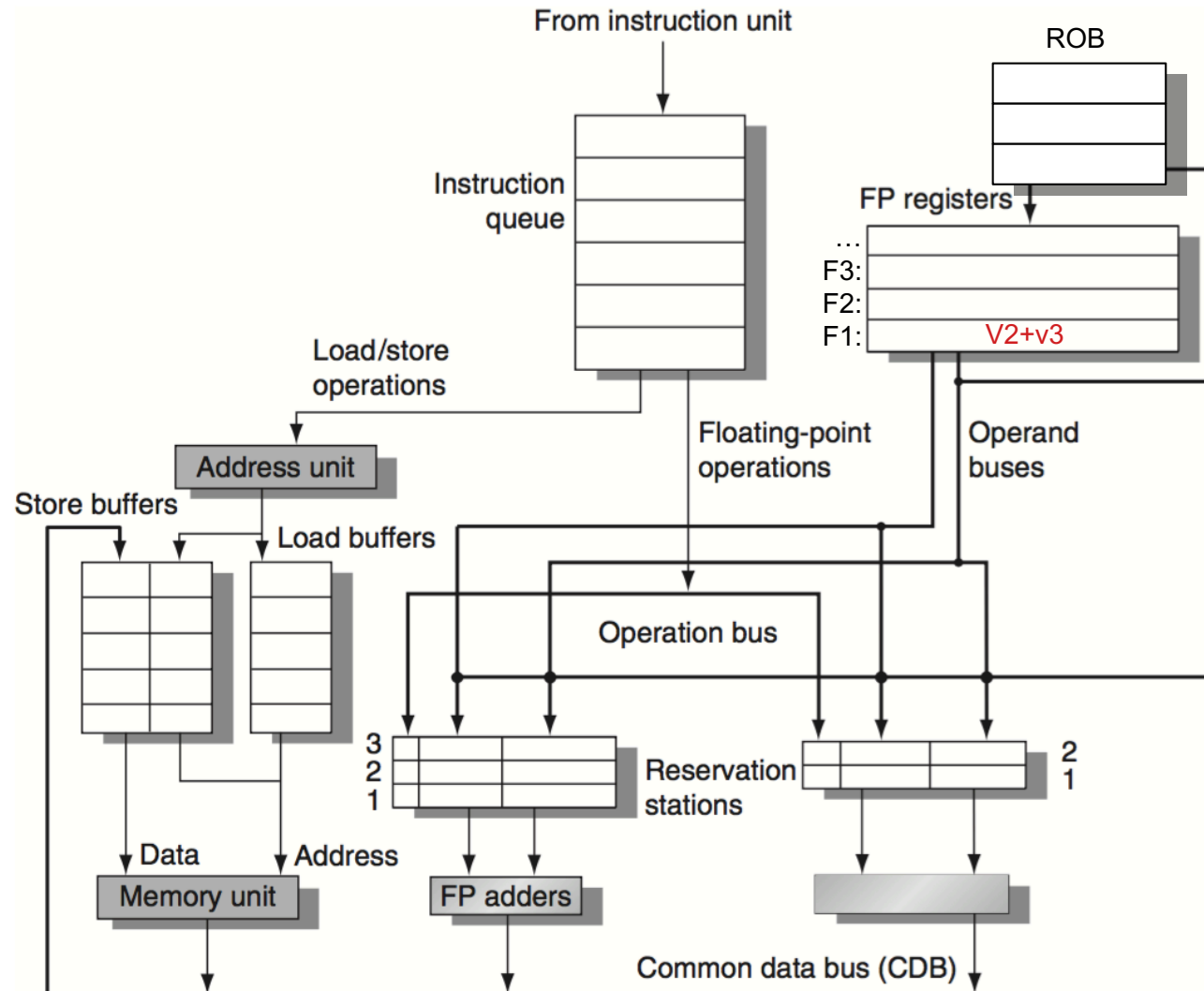
ROB Entry

| Valid | Result | Exception |
|-----------------|--------|-----------|
| | | |
| Program Counter | | |

Code

MUL F1, F2, F3

ADD F1, F2, F3



ROB Dependency Check

- Searching register values in AMD K-5

