

# U. Wisconsin CS/ECE 752

## Advanced Computer Architecture I

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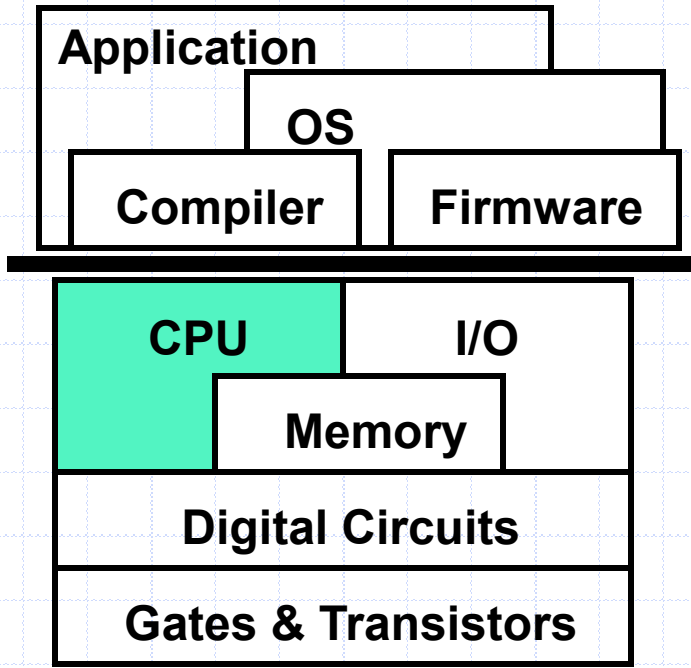
### Unit 5: Dynamic Scheduling I

Slides developed by Amir Roth of University of Pennsylvania with sources that included University of Wisconsin slides by Mark Hill, Guri Sohi, Jim Smith, and David Wood.

Slides enhanced by Milo Martin, Mark Hill, and David Wood with sources that included Profs. Asanovic, Falsafi, Hoe, Lipasti, Shen, Smith, Sohi, Vijaykumar, and Wood

# This Unit: Dynamic Scheduling I

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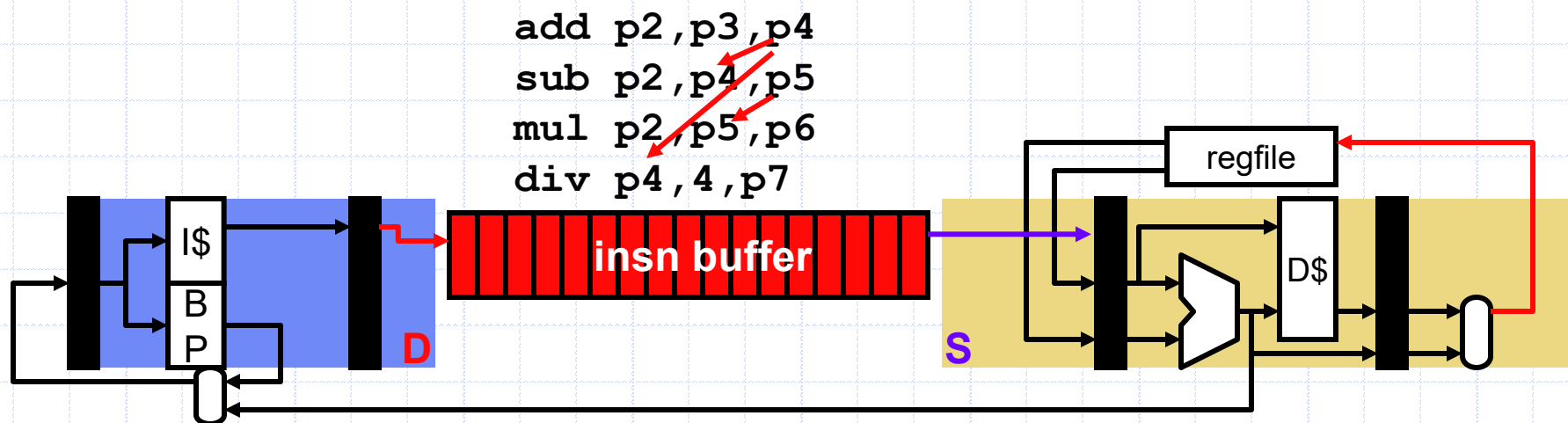
- Dynamic scheduling
  - Out-of-order execution
- Scoreboard
  - Dynamic scheduling with WAW/WAR
- Tomasulo's algorithm
  - Add register renaming to fix WAW/WAR
- Next unit
  - Adding speculation and precise state
  - Dynamic load scheduling

# The Problem With In-Order Pipelines

|                 | 1 | 2 | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-----------------|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| addf f0, f1, f2 | F | D | E+ | E+ | E+ | W  |    |    |    |    |    |    |    |    |    |    |
| mulf f2, f3, f2 |   | F | D  | d* | d* | E* | E* | E* | E* | E* | W  |    |    |    |    |    |
| subf f0, f1, f4 |   |   | F  | p* | p* | D  | E+ | E+ | E+ | W  |    |    |    |    |    |    |

- What's happening in cycle 4?
  - `mulf` stalls due to **RAW hazard**
    - OK, this is a fundamental problem
  - `subf` stalls due to **pipeline hazard**
    - Why? `subf` can't proceed into D because `mulf` is there
    - That is the only reason, and it isn't a fundamental one
- Why can't `subf` go into D in cycle 4 and E+ in cycle 6?

# Dynamic Scheduling: The Big Picture



Ready Table

| P2  | P3  | P4  | P5  | P6  | P7  |
|-----|-----|-----|-----|-----|-----|
| Yes | Yes |     |     |     |     |
| Yes | Yes | Yes |     |     | Yes |
| Yes | Yes | Yes | Yes |     | Yes |
| Yes | Yes | Yes | Yes | Yes | Yes |

`add p2, p3, p4`  
`sub p2, p4, p5` and `div p4, 4, p7`  
`mul p2, p5, p6`

Time

- Instructions fetch/decoded/renamed into *Instruction Buffer*
  - Also called "instruction window" or "instruction scheduler"
- Instructions (conceptually) check ready bits every cycle
  - Execute when ready

# Register Renaming

- To eliminate WAW and WAR hazards
- Example
  - Names: `r1, r2, r3`
  - Locations: `p1, p2, p3, p4, p5, p6, p7`
  - Original mapping: `r1`→`p1`, `r2`→`p2`, `r3`→`p3`, `p4`–`p7` are “free”

MapTable

| r1 | r2 | r3 |
|----|----|----|
| p1 | p2 | p3 |
| p4 | p2 | p3 |
| p4 | p2 | p5 |
| p4 | p2 | p6 |

FreeList

|                |
|----------------|
| p4, p5, p6, p7 |
| p5, p6, p7     |
| p6, p7         |
| p7             |

Raw insns

```
add r2, r3, r1
sub r2, r1, r3
mul r2, r3, r3
div r1, 4, r1
```

Renamed insns

```
add p2, p3, p4
sub p2, p4, p5
mul p2, p5, p6
div p4, 4, p7
```

- Renaming
  - + Removes **WAW** and **WAR** dependences
  - + Leaves **RAW** intact!

# Dynamic Scheduling - OoO Execution

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- Dynamic scheduling
  - Totally in the hardware
  - Also called “out-of-order execution” (OoO)
- Fetch many instructions into instruction window
  - Use branch prediction to speculate past (multiple) branches
  - Flush pipeline on branch misprediction
- Rename to avoid false dependencies (WAW and WAR)
- Execute instructions as soon as possible
  - Register dependencies are known
  - Handling memory dependencies more tricky (much more later)
- Commit instructions in order
  - Any strange happens before commit, just flush the pipeline
- Current machines: 200+ instruction scheduling window

# Static Instruction Scheduling

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- **Issue:** time at which insns execute
- **Schedule:** order in which insns execute
  - Related to issue, but the distinction is important
- **Scheduling:** re-arranging insns to enable rapid issue
  - Static: by compiler
  - Requires knowledge of pipeline and program dependences
    - **Pipeline scheduling:** the basics
  - Requires large scheduling scope full of independent insns
    - **Loop unrolling**, software pipelining: increase scope for loops
    - **Trace scheduling:** increase scope for non-loops

**Anything software can do ... hardware can do better**

# Motivation Dynamic Scheduling

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- **Dynamic scheduling (out-of-order execution)**
  - Execute insns in non-sequential (non-VonNeumann) order...
    - + Reduce RAW stalls
    - + Increase pipeline and functional unit (FU) utilization
      - Original motivation was to increase FP unit utilization
    - + Expose more opportunities for parallel issue (ILP)
      - Not in-order → can be in parallel
  - ...but make it appear like sequential execution
    - Important
      - But difficult
    - Next unit



# Before We Continue

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- If we can do this in software...
- ...why build complex (slow-clock, high-power) hardware?
  - + Performance portability
    - Don't want to recompile for new machines
  - + More information available
    - Memory addresses, branch directions, cache misses
  - + More registers available (??)
    - Compiler may not have enough to fix WAR/WAW hazards
  - + Easier to speculate and recover from mis-speculation
    - Flush instead of recover code
  - But compiler has a larger scope
    - Compiler does as much as it can (not much)
    - Hardware does the rest

# Going Forward: What's Next

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- We'll build this up in steps over the next several lectures
  - "Scoreboarding" - first OoO, no register renaming
  - "Tomasulo's algorithm" - adds register renaming
  - Handling precise state and speculation
    - P6-style execution (Intel Pentium Pro)
    - R10k-style execution (MIPS R10k)
  - Handling memory dependencies
    - Conservative and speculative
- Let's get started!

# Dynamic Scheduling as Loop Unrolling

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- Three steps of loop unrolling
  - Step I: combine iterations
    - Increase scheduling scope for more flexibility
  - Step II: pipeline schedule
    - Reduce impact of RAW hazards
  - Step III: rename registers
    - Remove WAR/WAW violations that result from scheduling

# Loop Example: SAX (SAXPY – PY)

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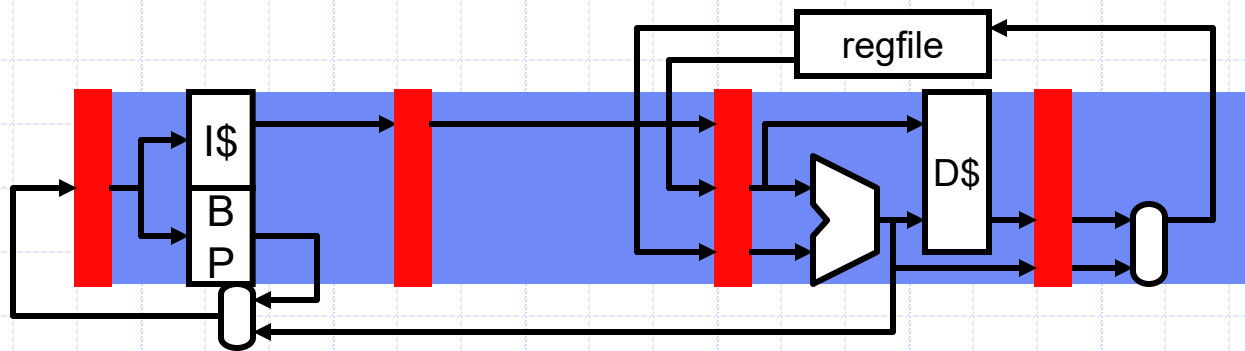
- **SAX** (Single-precision A X)
  - Only because there won't be room in the diagrams for SAXPY

```
for (i=0;i<N;i++)  
    Z[i]=A*X[i];
```

```
0: ldf X(r1),f1          // loop  
1: mulf f0,f1,f2         // A in f0  
2: stf f4,Z(r1)  
3: addi r1,4,r1          // i in r1  
4: blt r1,r2,0           // N*4 in r2
```

- Consider two iterations, ignore branch  
ldf, mulf, stf, addi, ldf, mulf, stf

# New Pipeline Terminology



- **In-order pipeline**
  - Often written as F,D,X,W (multi-cycle X includes M)
  - Example pipeline: 1-cycle int (including mem), 3-cycle pipelined FP

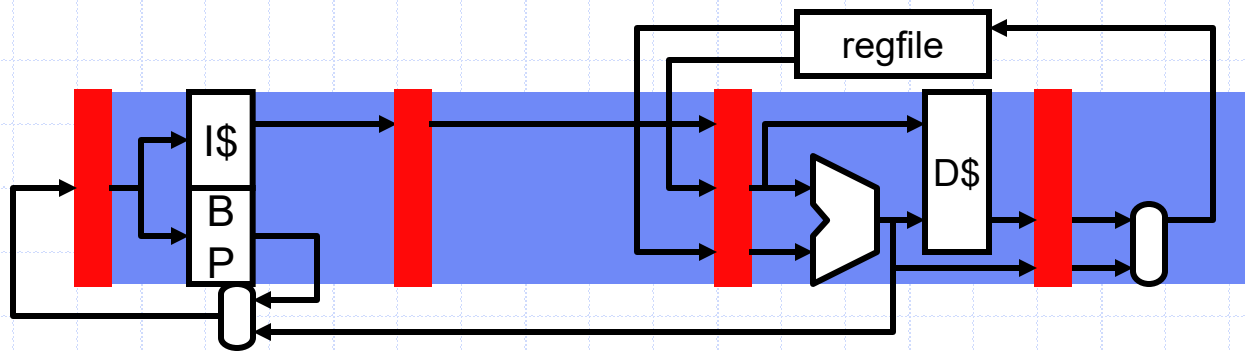
# New Pipeline Diagram

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| Insn          | D   | X    | W   |
|---------------|-----|------|-----|
| ldf X(r1),f1  | c1  | c2   | c3  |
| mulf f0,f1,f2 | c3  | c4+  | c7  |
| stf f2,Z(r1)  | c7  | c8   | c9  |
| addi r1,4,r1  | c8  | c9   | c10 |
| ldf X(r1),f1  | c10 | c11  | c12 |
| mulf f0,f1,f2 | c12 | c13+ | c16 |
| stf f2,Z(r1)  | c16 | c17  | c18 |

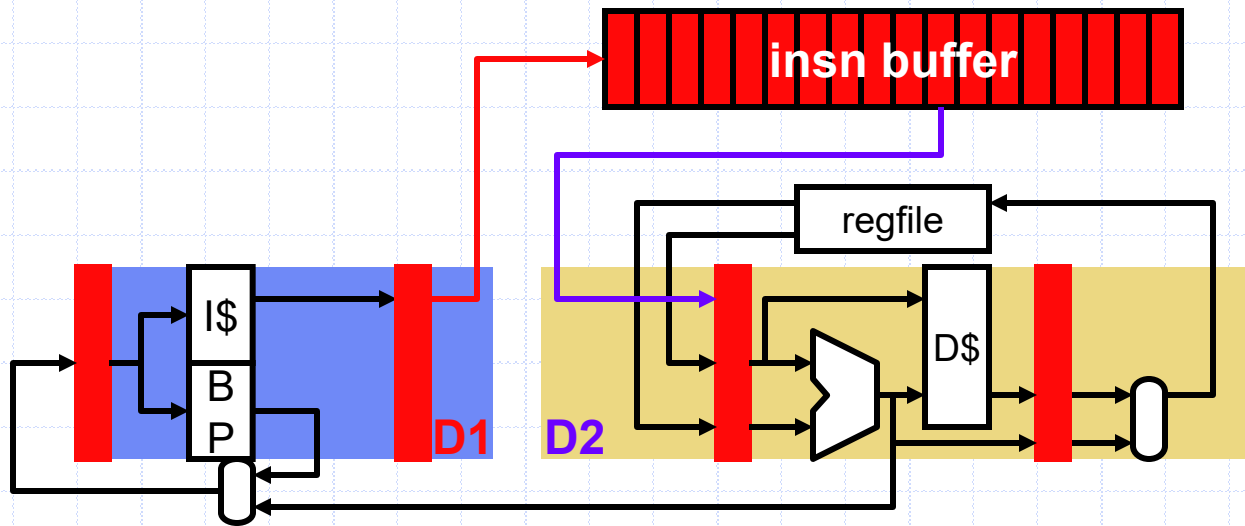
- Alternative pipeline diagram
  - Down: insns
  - Across: pipeline stages
  - In boxes: cycles
  - Basically: stages  $\leftrightarrow$  cycles
  - Convenient for out-of-order

# The Problem With In-Order Pipelines



- **In-order pipeline**
  - **Structural hazard:** 1 insn register (latch) per stage
    - 1 insn per stage per cycle (unless pipeline is replicated)
    - Younger insn can't "pass" older insn without "clobbering" it
- **Out-of-order pipeline**
  - Implement "passing" functionality by removing structural hazard

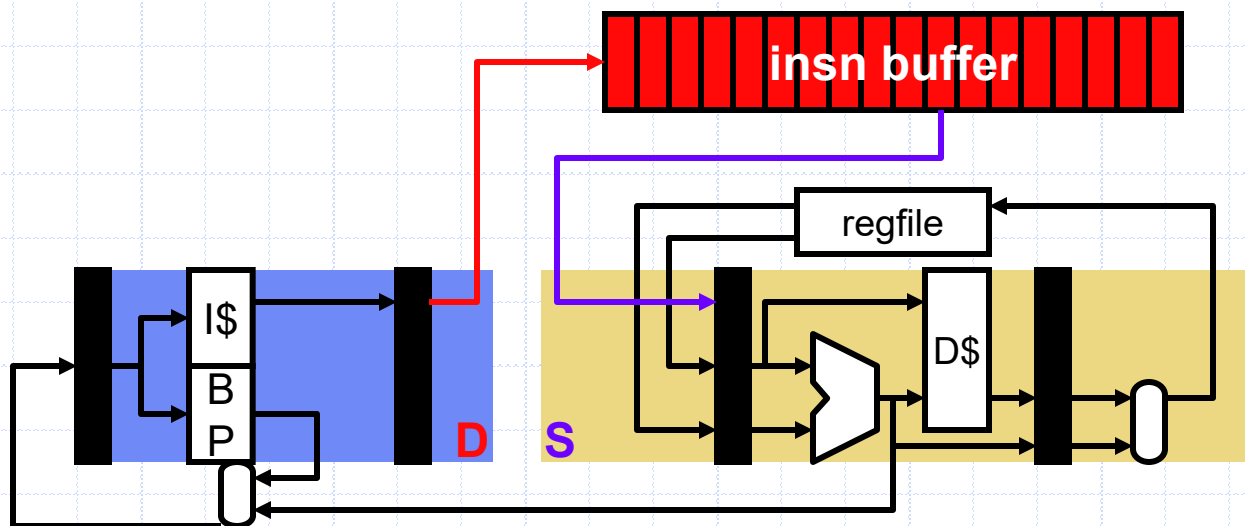
# Instruction Buffer



- Trick: **insn buffer** (many names for this buffer)
  - Basically: a bunch of latches for holding insns
  - Implements iteration fusing ... here is your scheduling scope
- Split D into two pieces
  - Accumulate decoded insns in buffer **in-order**
  - Buffer sends insns down rest of pipeline **out-of-order**

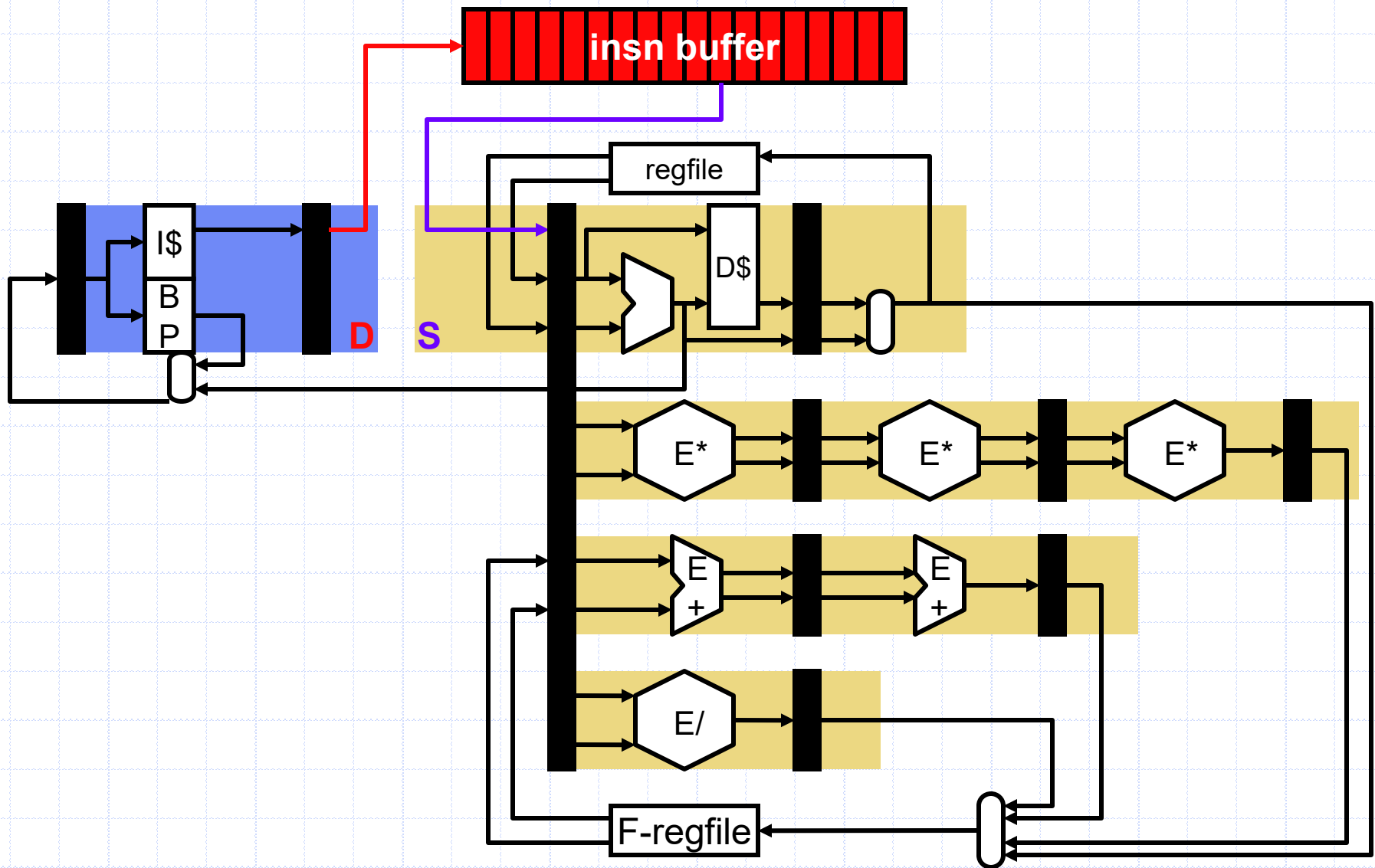


# Dispatch and Issue



- **Dispatch (D)**: first part of decode
  - Allocate slot in insn buffer
    - New kind of structural hazard (insn buffer is full)
  - In order: **stall** back-propagates to younger insns
- **Issue (S)**: second part of decode
  - Send insns from insn buffer to execution units
  - + Out-of-order: **wait** doesn't back-propagate to younger insns

# Dispatch and Issue with Floating-Point



# Dynamic Scheduling Algorithms

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- Three parts to loop unrolling
  - Scheduling scope: insn buffer
  - Pipeline scheduling and register renaming: **scheduling algorithm**
- Look at two register scheduling algorithms
  - **Register scheduler**: scheduler based on register dependences
  - Scoreboard
    - No register renaming → limited scheduling flexibility
  - Tomasulo
    - Register renaming → more flexibility, better performance
- Big simplification in this unit: **memory scheduling**
  - Pretend register algorithm magically knows memory dependences
  - A little more realism next unit

# Scheduling Algorithm I: Scoreboard

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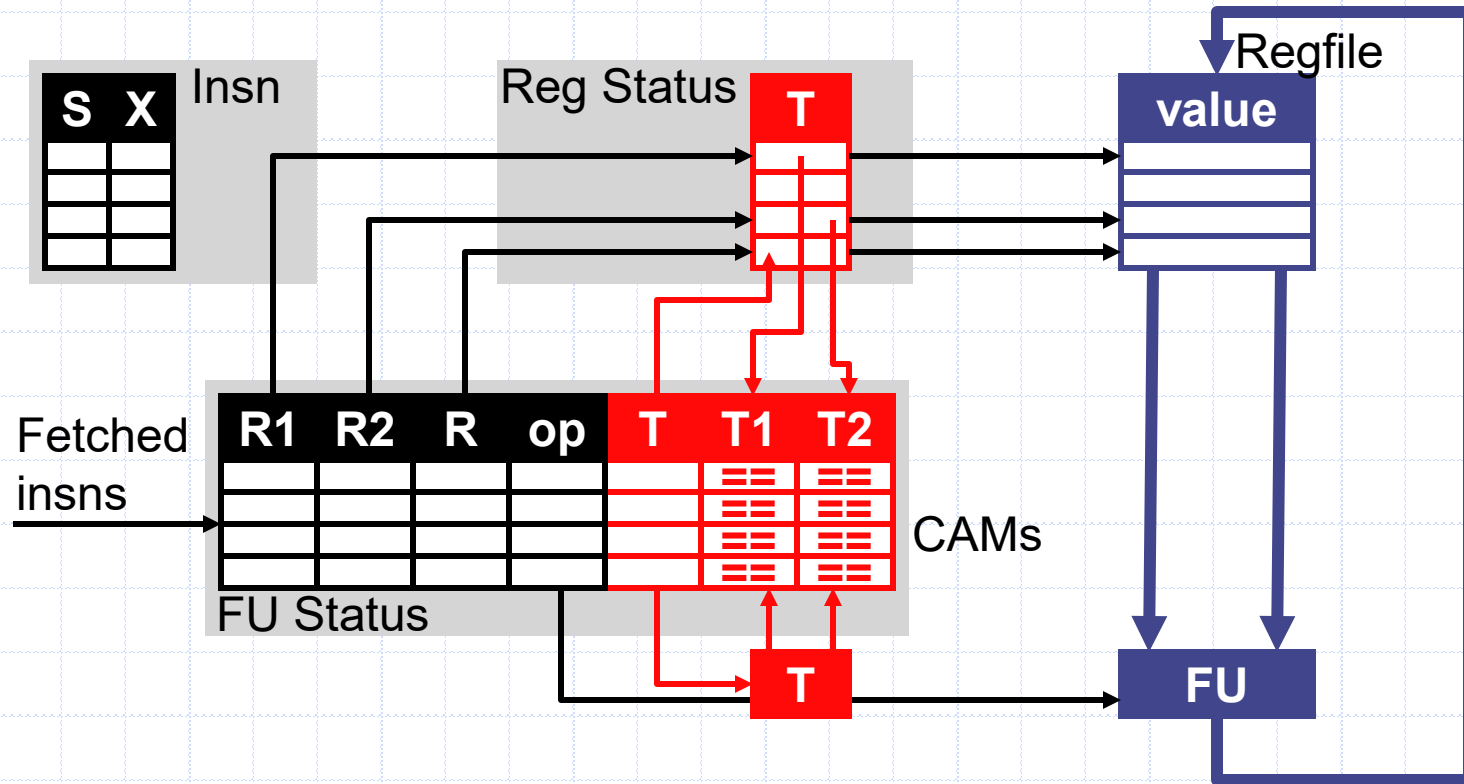
- **Scoreboard**
  - Centralized control scheme: insn status explicitly tracked
  - Insn buffer: **Functional Unit Status Table (FUST)**
- First implementation: CDC 6600 [1964]
  - 16 separate non-pipelined functional units (7 int, 4 FP, 5 mem)
  - No register bypassing
- Our example: "Simple Scoreboard"
  - 5 FU: 1 ALU, 1 load, 1 store, 2 FP (3-cycle, pipelined)

# Scoreboard Data Structures

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- FU Status Table
  - **FU, busy, op, R, R1, R2**: destination/source register names
  - **T**: destination register tag (FU producing the value)
  - **T1, T2**: source register tags (FU producing the values)
- Register Status Table
  - **T**: tag (FU that will write this register)
- Tags interpreted as ready-bits
  - Tag == 0 → Value is ready in register file
  - Tag != 0 → Value is not ready, will be supplied by T
- Insn status table
  - S,X bits for all active insns

# Simple Scoreboard Data Structures



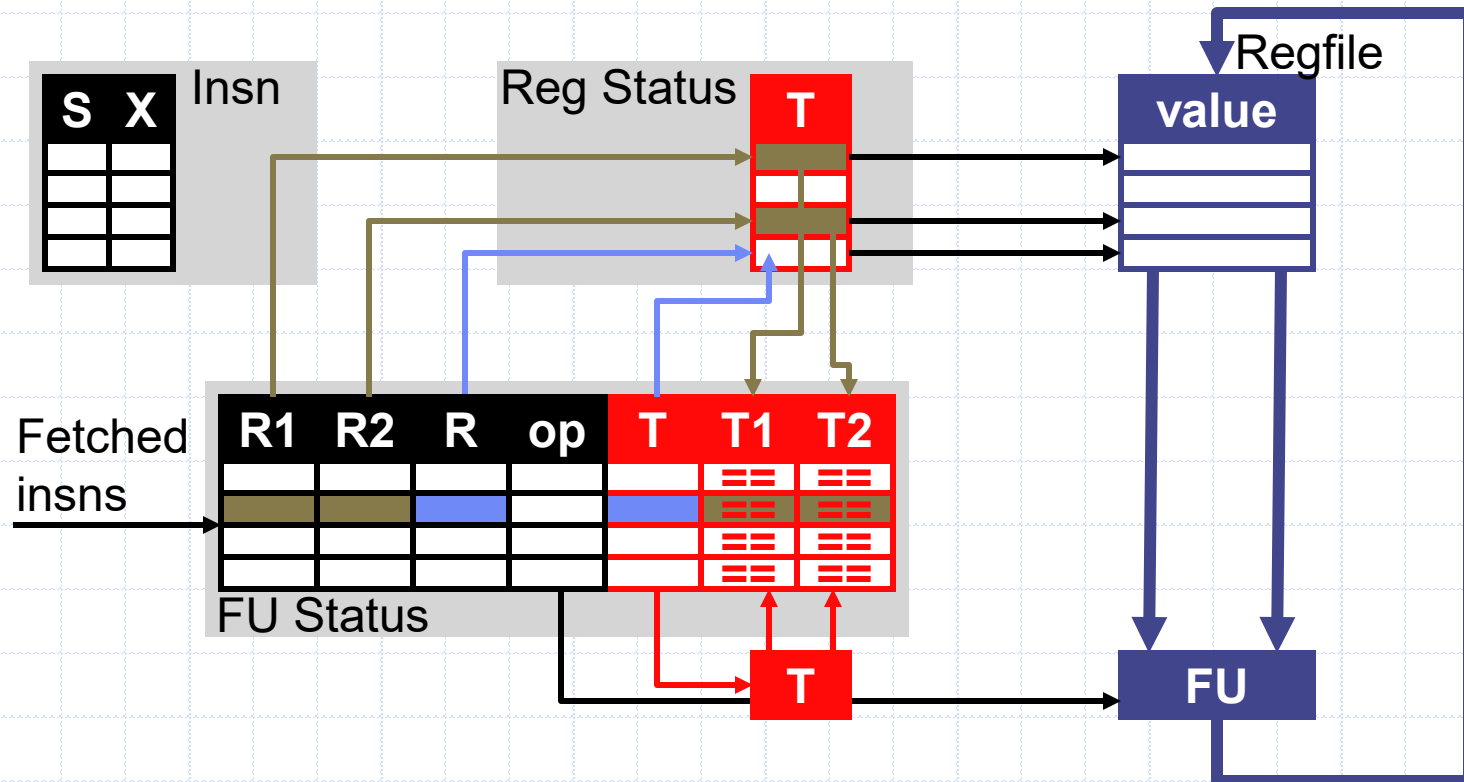
- Insns fields and status bits
- **Tags**
- **Values**

# Scoreboard Pipeline

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- New pipeline structure: F, **D**, **S**, X, **W**
  - F (fetch)
    - Same as it ever was
  - **D (dispatch)**
    - **Structural** or **WAW** hazard ? **stall** : allocate scoreboard entry
  - **S (issue)**
    - **RAW** hazard ? **wait** : read registers, go to execute
  - X (execute)
    - Execute operation, notify scoreboard when done
  - **W (writeback)**
    - **WAR** hazard ? **wait** : write register, free scoreboard entry
    - W and RAW-dependent S in same cycle
    - W and structural-dependent D in same cycle

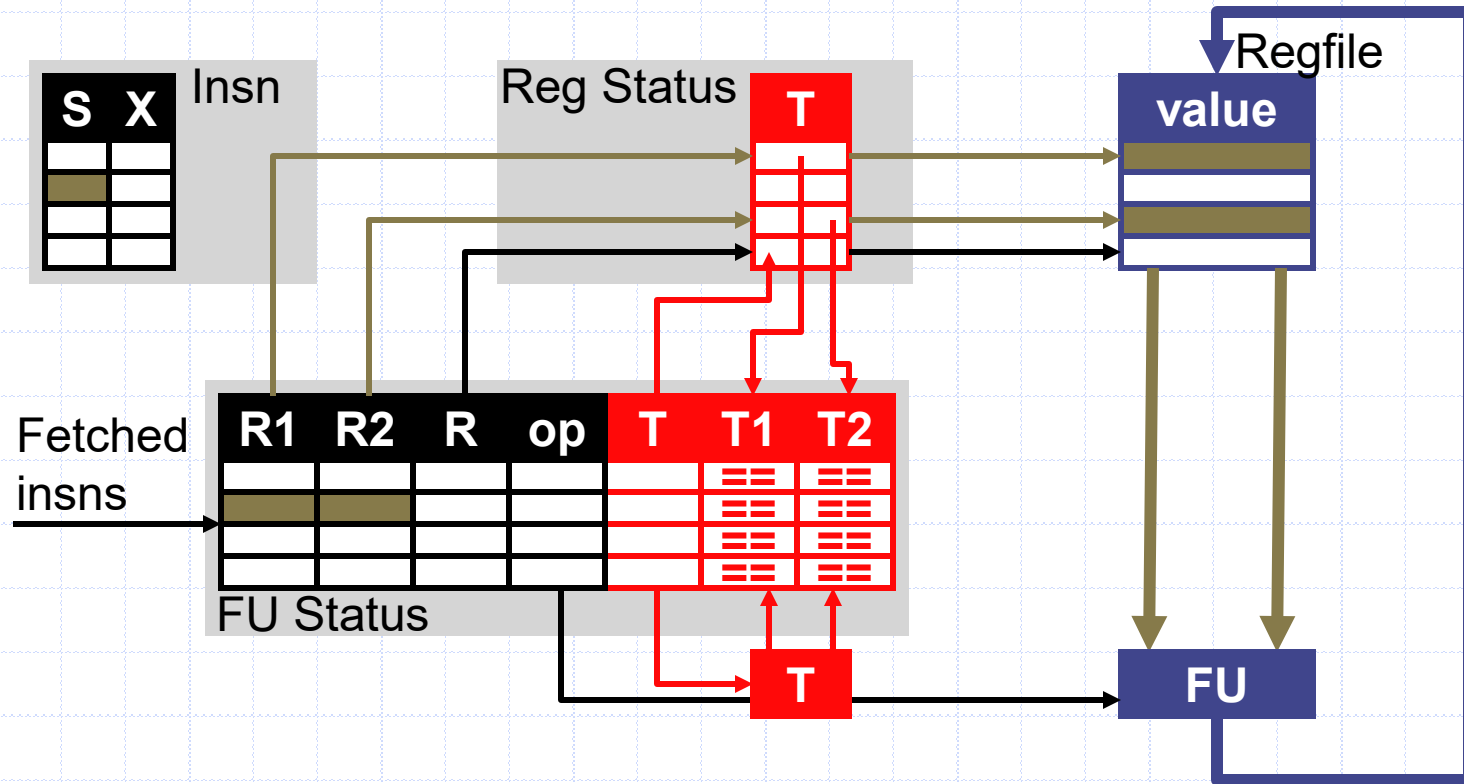
# Scoreboard Dispatch (D)



- Stall for WAW or structural (Scoreboard, FU) hazards
  - Allocate scoreboard entry
  - Copy Reg Status for input registers
  - Set Reg Status for output register



# Scoreboard Issue (S)



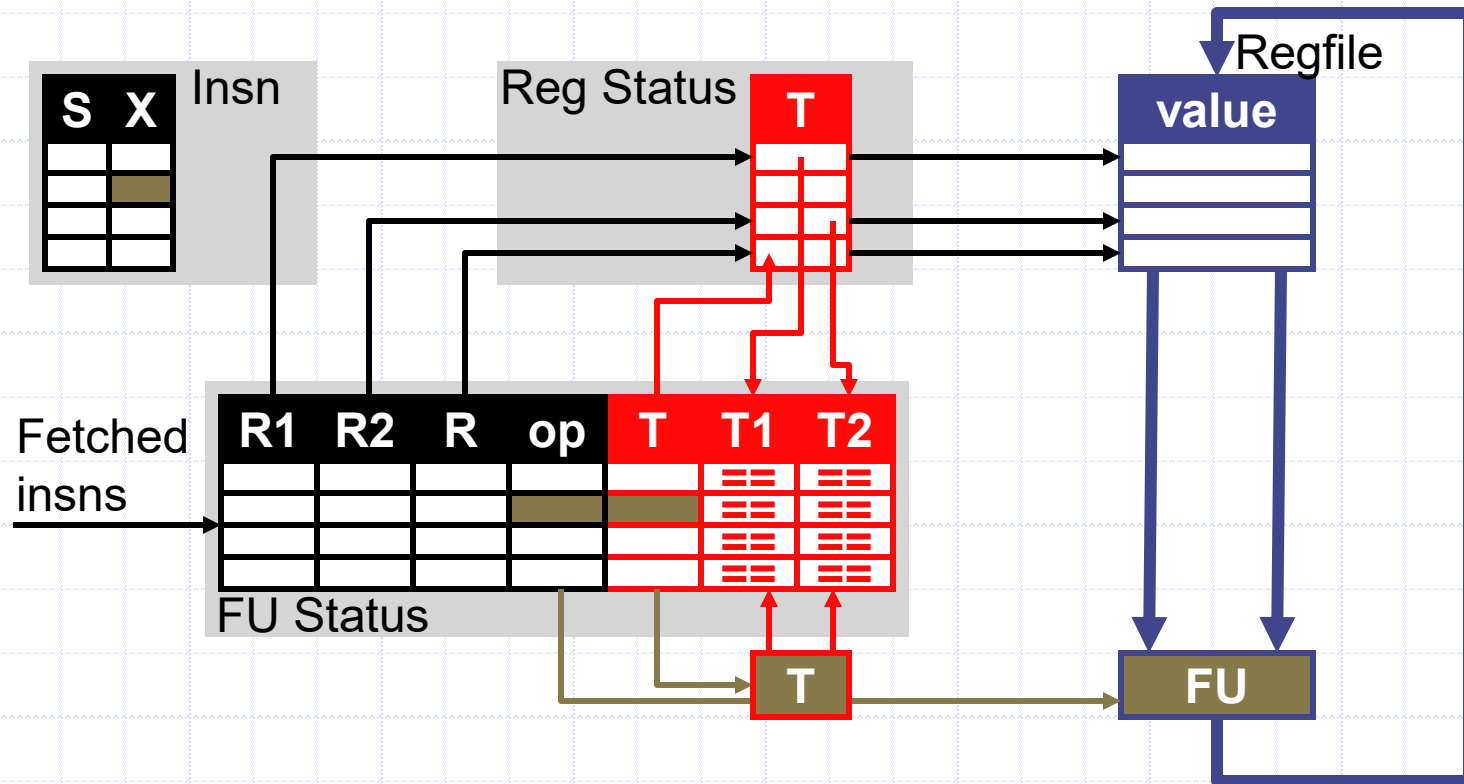
- Wait for RAW register hazards
  - Read registers

# Issue Policy and Issue Logic

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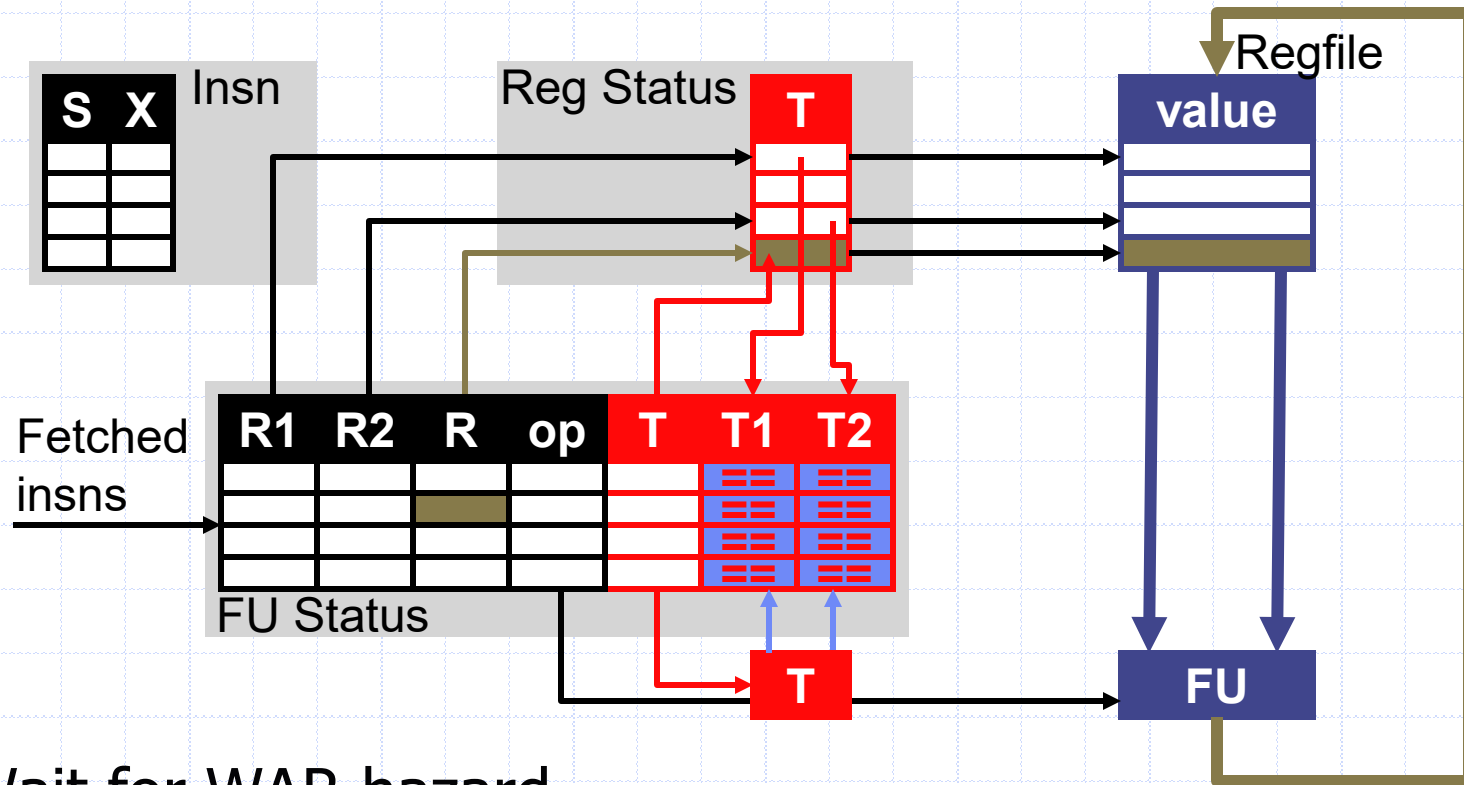
- Issue
  - If multiple insns ready, which one to choose? **Issue policy**
    - Oldest first? Safe
    - Longest latency first? May yield better performance
  - **Select logic**: implements issue policy
    - $W \rightarrow 1$  priority encoder
    - **W**: window size (number of scoreboard entries)

# Scoreboard Execute (X)



- Execute insn

# Scoreboard Writeback (W)



- Wait for WAR hazard
  - Write value into regfile, clear Reg Status entry
  - Compare tag to waiting insns input tags, match ? clear input tag
  - Free scoreboard entry

# Scoreboard Data Structures

| Insn Status   |   |   |   |   |
|---------------|---|---|---|---|
| Insn          | D | S | X | W |
| ldf X(r1),f1  |   |   |   |   |
| mulf f0,f1,f2 |   |   |   |   |
| stf f2,Z(r1)  |   |   |   |   |
| addi r1,4,r1  |   |   |   |   |
| ldf X(r1),f1  |   |   |   |   |
| mulf f0,f1,f2 |   |   |   |   |
| stf f2,Z(r1)  |   |   |   |   |

| Reg Status |   |
|------------|---|
| Reg        | T |
| f0         |   |
| f1         |   |
| f2         |   |
| r1         |   |

| FU Status |      |    |   |    |    |    |    |
|-----------|------|----|---|----|----|----|----|
| FU        | busy | op | R | R1 | R2 | T1 | T2 |
| ALU       | no   |    |   |    |    |    |    |
| LD        | no   |    |   |    |    |    |    |
| ST        | no   |    |   |    |    |    |    |
| FP1       | no   |    |   |    |    |    |    |
| FP2       | no   |    |   |    |    |    |    |

# Scoreboard: Cycle 1

| Insn Status     |    |   |   |   |
|-----------------|----|---|---|---|
| Insn            | D  | S | X | W |
| ldf X(r1), f1   | c1 |   |   |   |
| mulf f0, f1, f2 |    |   |   |   |
| stf f2, Z(r1)   |    |   |   |   |
| addi r1, 4, r1  |    |   |   |   |
| ldf X(r1), f1   |    |   |   |   |
| mulf f0, f1, f2 |    |   |   |   |
| stf f2, Z(r1)   |    |   |   |   |

| Reg Status |    |
|------------|----|
| Reg        | T  |
| f0         |    |
| f1         | LD |
| f2         |    |
| r1         |    |

| FU Status |      |     |    |    |    |    |    |
|-----------|------|-----|----|----|----|----|----|
| FU        | busy | op  | R  | R1 | R2 | T1 | T2 |
| ALU       | no   |     |    |    |    |    |    |
| LD        | yes  | ldf | f1 | -  | r1 | -  | -  |
| ST        | no   |     |    |    |    |    |    |
| FP1       | no   |     |    |    |    |    |    |
| FP2       | no   |     |    |    |    |    |    |

allocate

# Scoreboard: Cycle 2

| Insn Status     |    |    |   |   |
|-----------------|----|----|---|---|
| Insn            | D  | S  | X | W |
| ldf X(r1), f1   | c1 | c2 |   |   |
| mulf f0, f1, f2 | c2 |    |   |   |
| stf f2, Z(r1)   |    |    |   |   |
| addi r1, 4, r1  |    |    |   |   |
| ldf X(r1), f1   |    |    |   |   |
| mulf f0, f1, f2 |    |    |   |   |
| stf f2, Z(r1)   |    |    |   |   |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP1 |
| r1         |     |

| FU Status |      |      |    |    |    |    |    |
|-----------|------|------|----|----|----|----|----|
| FU        | busy | op   | R  | R1 | R2 | T1 | T2 |
| ALU       | no   |      |    |    |    |    |    |
| LD        | yes  | ldf  | f1 | -  | r1 | -  | -  |
| ST        | no   |      |    |    |    |    |    |
| FP1       | yes  | mulf | f2 | f0 | f1 | -  | LD |
| FP2       | no   |      |    |    |    |    |    |

allocate

# Scoreboard: Cycle 3

| Insn Status     |    |    |    |   |
|-----------------|----|----|----|---|
| Insn            | D  | S  | X  | W |
| ldf X(r1), f1   | c1 | c2 | c3 |   |
| mulf f0, f1, f2 | c2 |    |    |   |
| stf f2, Z(r1)   | c3 |    |    |   |
| addi r1, 4, r1  |    |    |    |   |
| ldf X(r1), f1   |    |    |    |   |
| mulf f0, f1, f2 |    |    |    |   |
| stf f2, Z(r1)   |    |    |    |   |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP1 |
| r1         |     |

| Functional unit status |      |      |    |    |    |     |    |
|------------------------|------|------|----|----|----|-----|----|
| FU                     | busy | op   | R  | R1 | R2 | T1  | T2 |
| ALU                    | no   |      |    |    |    |     |    |
| LD                     | yes  | ldf  | f1 | -  | r1 | -   | -  |
| ST                     | yes  | stf  | -  | f2 | r1 | FP1 | -  |
| FP1                    | yes  | mulf | f2 | f0 | f1 | -   | LD |
| FP2                    | no   |      |    |    |    |     |    |

allocate



# Scoreboard: Cycle 4

| Insn Status     |    |    |    |    |
|-----------------|----|----|----|----|
| Insn            | D  | S  | X  | W  |
| ldf X(r1), f1   | c1 | c2 | c3 | c4 |
| mulf f0, f1, f2 | c2 | c4 |    |    |
| stf f2, Z(r1)   | c3 |    |    |    |
| addi r1, 4, r1  | c4 |    |    |    |
| ldf X(r1), f1   |    |    |    |    |
| mulf f0, f1, f2 |    |    |    |    |
| stf f2, Z(r1)   |    |    |    |    |

| Reg Status |           |
|------------|-----------|
| Reg        | T         |
| f0         |           |
| f1         | <u>LD</u> |
| f2         | FP1       |
| r1         | ALU       |

f1 written → clear

| FU Status |      |      |    |    |    |     |           |
|-----------|------|------|----|----|----|-----|-----------|
| FU        | busy | op   | R  | R1 | R2 | T1  | T2        |
| ALU       | yes  | addi | r1 | r1 | -  | -   | -         |
| LD        | no   |      |    |    |    |     |           |
| ST        | yes  | stf  | -  | f2 | r1 | FP1 | -         |
| FP1       | yes  | mulf | f2 | f0 | f1 | -   | <u>LD</u> |
| FP2       | no   |      |    |    |    |     |           |

allocate  
free

f0 (LD) is ready → issue mulf

# Scoreboard: Cycle 5

| Insn Status   |    |    |    |    |
|---------------|----|----|----|----|
| Insn          | D  | S  | X  | W  |
| ldf X(r1),f1  | c1 | c2 | c3 | c4 |
| mulf f0,f1,f2 | c2 | c4 | c5 |    |
| stf f2,Z(r1)  | c3 |    |    |    |
| addi r1,4,r1  | c4 | c5 |    |    |
| ldf X(r1),f1  | c5 |    |    |    |
| mulf f0,f1,f2 |    |    |    |    |
| stf f2,Z(r1)  |    |    |    |    |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP1 |
| r1         | ALU |

| FU Status |      |      |    |    |    |     |     |
|-----------|------|------|----|----|----|-----|-----|
| FU        | busy | op   | R  | R1 | R2 | T1  | T2  |
| ALU       | yes  | addi | r1 | r1 | -  | -   | -   |
| LD        | yes  | ldf  | f1 | -  | r1 | -   | ALU |
| ST        | yes  | stf  | -  | f2 | r1 | FP1 | -   |
| FP1       | yes  | mulf | f2 | f0 | f1 | -   | -   |
| FP2       | no   |      |    |    |    |     |     |

allocate

# Scoreboard: Cycle 6

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ |    |
| stf f2, Z(r1)   | c3 |    |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  |    |
| ldf X(r1), f1   | c5 |    |     |    |
| mulf f0, f1, f2 |    |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP1 |
| r1         | ALU |

**D stall: WAW hazard w/ mulf (f2)**  
**How to tell? RegStatus[f2] non-empty**

| FU Status |      |      |    |    |    |     |     |
|-----------|------|------|----|----|----|-----|-----|
| FU        | busy | op   | R  | R1 | R2 | T1  | T2  |
| ALU       | yes  | addi | r1 | r1 | -  | -   | -   |
| LD        | yes  | ldf  | f1 | -  | r1 | -   | ALU |
| ST        | yes  | stf  | -  | f2 | r1 | FP1 | -   |
| FP1       | yes  | mulf | f2 | f0 | f1 | -   | -   |
| FP2       | no   |      |    |    |    |     |     |

# Scoreboard: Cycle 7

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ |    |
| stf f2, Z(r1)   | c3 |    |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  |    |
| ldf X(r1), f1   | c5 |    |     |    |
| mulf f0, f1, f2 |    |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP1 |
| r1         | ALU |

W wait: WAR hazard w/ stf (r1)  
How to tell? Untagged r1 in FuStatus  
Requires CAM

| FU Status |      |      |    |    |    |     |     |
|-----------|------|------|----|----|----|-----|-----|
| FU        | busy | op   | R  | R1 | R2 | T1  | T2  |
| ALU       | yes  | addi | r1 | r1 | -  | -   | -   |
| LD        | yes  | ldf  | f1 | -  | r1 | -   | ALU |
| ST        | yes  | stf  | -  | f2 | r1 | FP1 | -   |
| FP1       | yes  | mulf | f2 | f0 | f1 | -   | -   |
| FP2       | no   |      |    |    |    |     |     |

# Scoreboard: Cycle 8

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ | c8 |
| stf f2, Z(r1)   | c3 | c8 |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  |    |
| ldf X(r1), f1   | c5 |    |     |    |
| mulf f0, f1, f2 | c8 |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Reg Status |                |
|------------|----------------|
| Reg        | T              |
| f0         |                |
| f1         | LD             |
| f2         | <u>FP1</u> FP2 |
| r1         | ALU            |

first mulf done (FP1)

W wait

| FU Status |      |      |    |    |    |            |     |
|-----------|------|------|----|----|----|------------|-----|
| FU        | busy | op   | R  | R1 | R2 | T1         | T2  |
| ALU       | yes  | addi | r1 | r1 | -  | -          | -   |
| LD        | yes  | ldf  | f1 | -  | r1 | -          | ALU |
| ST        | yes  | stf  | -  | f2 | r1 | <u>FP1</u> | -   |
| FP1       | no   |      |    |    |    |            |     |
| FP2       | yes  | mulf | f2 | f0 | f1 | -          | LD  |

f1 (FP1) is ready → issue stf  
free  
allocate

# Scoreboard: Cycle 9

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ | c8 |
| stf f2, Z(r1)   | c3 | c8 | c9  |    |
| addi r1, 4, r1  | c4 | c5 | c6  | c9 |
| ldf X(r1), f1   | c5 | c9 |     |    |
| mulf f0, f1, f2 | c8 |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Reg Status |            |
|------------|------------|
| Reg        | T          |
| f0         |            |
| f1         | LD         |
| f2         | FP2        |
| r1         | <u>ALU</u> |

r1 written → clear

D stall: structural hazard FuStatus [ST]

| FU Status  |      |      |    |    |    |    |            |
|------------|------|------|----|----|----|----|------------|
| FU         | busy | op   | R  | R1 | R2 | T1 | T2         |
| <u>ALU</u> | no   |      |    |    |    |    |            |
| LD         | yes  | ldf  | f1 | -  | r1 | -  | <u>ALU</u> |
| ST         | yes  | stf  | -  | f2 | r1 | -  | -          |
| FP1        | no   |      |    |    |    |    |            |
| FP2        | yes  | mulf | f2 | f0 | f1 | -  | LD         |

free

r1 (ALU) is ready → issue ldf

# Scoreboard: Cycle 10

| Insn Status     |     |    |     |     |
|-----------------|-----|----|-----|-----|
| Insn            | D   | S  | X   | W   |
| ldf X(r1), f1   | c1  | c2 | c3  | c4  |
| mulf f0, f1, f2 | c2  | c4 | c5+ | c8  |
| stf f2, Z(r1)   | c3  | c8 | c9  | c10 |
| addi r1, 4, r1  | c4  | c5 | c6  | c9  |
| ldf X(r1), f1   | c5  | c9 | c10 |     |
| mulf f0, f1, f2 | c8  |    |     |     |
| stf f2, Z(r1)   | c10 |    |     |     |

| Reg Status |     |
|------------|-----|
| Reg        | T   |
| f0         |     |
| f1         | LD  |
| f2         | FP2 |
| r1         |     |

**W & structural-dependent D in same cycle**

| FU Status |      |      |    |    |    |     |    |
|-----------|------|------|----|----|----|-----|----|
| FU        | busy | op   | R  | R1 | R2 | T1  | T2 |
| ALU       | no   |      |    |    |    |     |    |
| LD        | yes  | ldf  | f1 | -  | r1 | -   | -  |
| ST        | yes  | stf  | -  | f2 | r1 | FP2 | -  |
| FP1       | no   |      |    |    |    |     |    |
| FP2       | yes  | mulf | f2 | f0 | f1 | -   | LD |

**free, then allocate**

# In-Order vs. Scoreboard

|               | In-Order |      |     | Scoreboard |     |      |     |
|---------------|----------|------|-----|------------|-----|------|-----|
| Insn          | D        | X    | W   | D          | S   | X    | W   |
| ldf X(r1),f1  | c1       | c2   | c3  | c1         | c2  | c3   | c4  |
| mulf f0,f1,f2 | c3       | c4+  | c7  | c2         | c4  | c5+  | c8  |
| stf f2,Z(r1)  | c7       | c8   | c9  | c3         | c8  | c9   | c10 |
| addi r1,4,r1  | c8       | c9   | c10 | c4         | c5  | c6   | c9  |
| ldf X(r1),f1  | c10      | c11  | c12 | c5         | c9  | c10  | c11 |
| mulf f0,f1,f2 | c12      | c13+ | c16 | c8         | c11 | c12+ | c15 |
| stf f2,Z(r1)  | c16      | c17  | c18 | c10        | c15 | c16  | c17 |

- Big speedup?
  - Only 1 cycle advantage for scoreboard
    - Why? **addi** WAR hazard
    - Scoreboard issued **addi** earlier (c8 → c5)
    - But WAR hazard delayed W until c9
    - Delayed issue of second iteration



# In-Order vs. Scoreboard II: Cache Miss

| Insn          | In-Order |      |     | Scoreboard |     |      |     |
|---------------|----------|------|-----|------------|-----|------|-----|
|               | D        | X    | W   | D          | S   | X    | W   |
| ldf X(r1),f1  | c1       | c2+  | c7  | c1         | c2  | c3+  | c8  |
| mulf f0,f1,f2 | c7       | c8+  | c11 | c2         | c8  | c9+  | c12 |
| stf f2,Z(r1)  | c11      | c12  | c13 | c3         | c12 | c13  | c14 |
| addi r1,4,r1  | c12      | c13  | c14 | c4         | c5  | c6   | c13 |
| ldf X(r1),f1  | c14      | c15  | c16 | c5         | c13 | c14  | c15 |
| mulf f0,f1,f2 | c16      | c17+ | c20 | c6         | c15 | c16+ | c19 |
| stf f2,Z(r1)  | c20      | c21  | c22 | c7         | c19 | c20  | c21 |

- Assume
  - 5 cycle cache miss on first `ldf`
  - Ignore FUST structural hazards
    - Little relative advantage
      - `addi` **WAR hazard** ( $c7 \rightarrow c13$ ) stalls second iteration

# Scoreboard Redux

---

- The good
  - + Cheap hardware
    - InsnStatus + FuStatus + RegStatus  $\sim$  1 FP unit in area
  - + Pretty good performance
    - 1.7X for FORTRAN (scientific array) programs
- The less good
  - No bypassing
    - Is this a fundamental problem?
  - Limited scheduling scope
    - Structural/**WAW** hazards delay dispatch
  - Slow issue of truly-dependent (RAW) insns
    - **WAR** hazards delay writeback
  - Fix with **hardware register renaming**

# Register Renaming

---

- **Register renaming (in hardware)**
  - Change register names to eliminate WAR/WAW hazards
  - An elegant idea (like caching & pipelining)
  - Key: think of registers (`r1, f0...`) as **names**, not **storage locations**
    - + Can have more locations than names
    - + Can have multiple active versions of same name
- How does it work?
  - **Map-table**: maps names to most recent locations
    - SRAM indexed by name
  - On a write: allocate new location, note in map-table
  - On a read: find location of most recent write via map-table lookup
  - Small detail: must de-allocate locations at some point

# Register Renaming Example

- Parameters

- Names: `r1, r2, r3`
- Locations: `p1, p2, p3, p4, p5, p6, p7`
- Original mapping: `r1→p1, r2→p2, r3→p3`, `p4–p7` are “free”

MapTable

| r1 | r2 | r3 |
|----|----|----|
| p1 | p2 | p3 |
| p4 | p2 | p3 |
| p4 | p2 | p5 |
| p4 | p2 | p6 |

FreeList

|                |
|----------------|
| p4, p5, p6, p7 |
| p5, p6, p7     |
| p6, p7         |
| p7             |

Raw insns

```
add r2, r3, r1
sub r2, r1, r3
mul r2, r3, r3
div r1, 4, r1
```

Renamed insns

```
add p2, p3, p4
sub p2, p4, p5
mul p2, p5, p6
div p4, 4, p7
```

- Renaming

- + Removes **WAW** and **WAR** dependences
- + Leaves **RAW** intact!

# Scheduling Algorithm II: Tomasulo

---

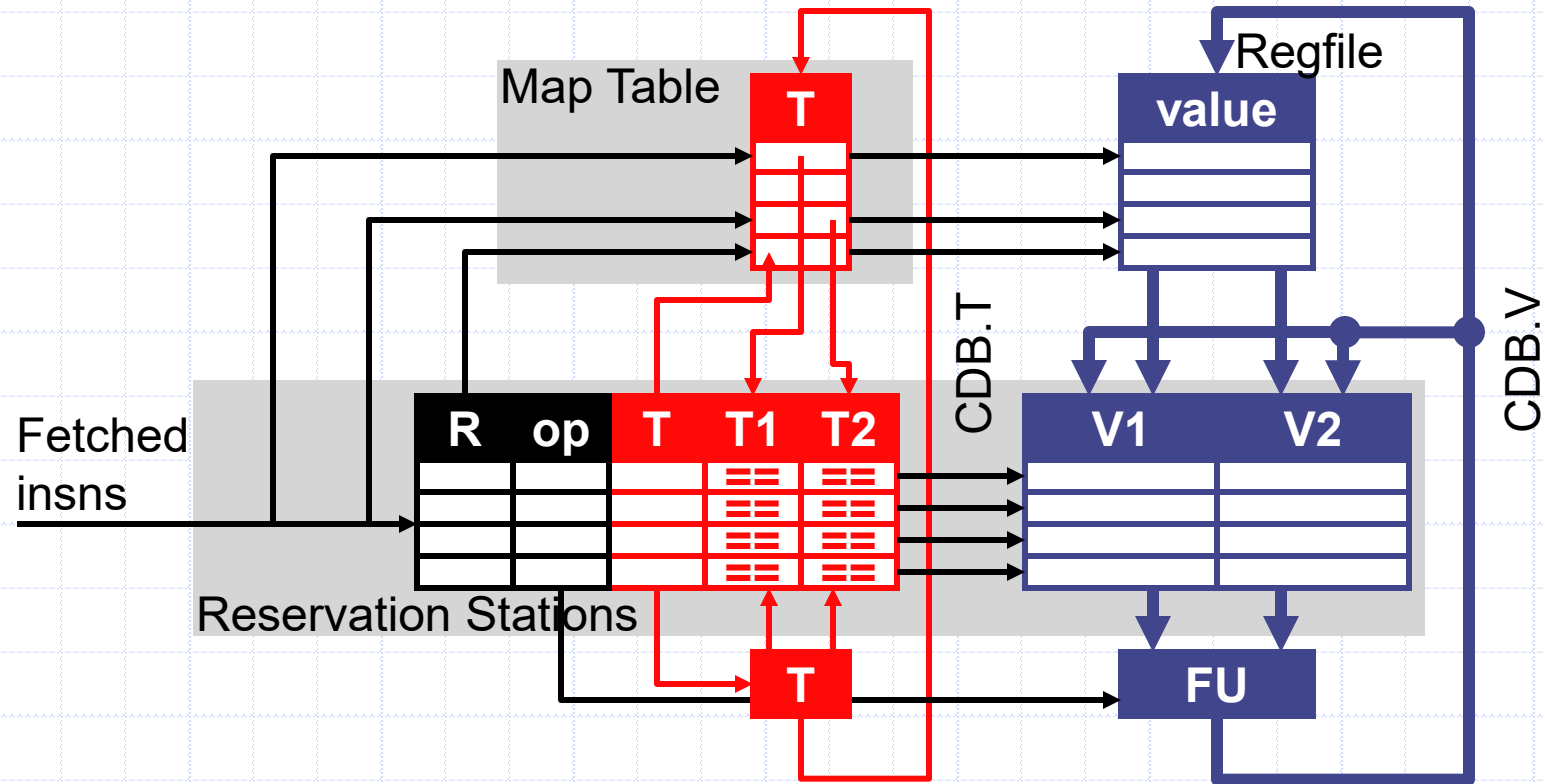
- **Tomasulo's algorithm**
  - **Reservation stations (RS)**: instruction buffer
  - **Common data bus (CDB)**: broadcasts results to RS
  - Register renaming: removes WAR/WAW hazards
- First implementation: IBM 360/91 [1967]
  - Dynamic scheduling for FP units only
  - Bypassing
- Our example: "Simple Tomasulo"
  - Dynamic scheduling for everything, including load/store
  - No bypassing (for comparison with Scoreboard)
  - 5 RS: 1 ALU, 1 load, 1 store, 2 FP (3-cycle, pipelined)

# Tomasulo Data Structures

---

- Reservation Stations (RS#)
  - **FU, busy, op, R**: destination register name
  - **T**: destination register tag (RS# of this RS)
  - **T1, T2**: source register tags (RS# of RS that will produce value)
  - **V1, V2**: source register values
    - That's new
- Map Table
  - **T**: tag (RS#) that will write this register
- Common Data Bus (CDB)
  - Broadcasts <RS#, value> of completed insns
- Tags interpreted as ready-bits++
  - $T=0 \rightarrow$  Value is ready somewhere
  - $T \neq 0 \rightarrow$  Value is not ready, wait until CDB broadcasts T

# Simple Tomasulo Data Structures



- Insn fields and status bits
- **Tags**
- **Values**

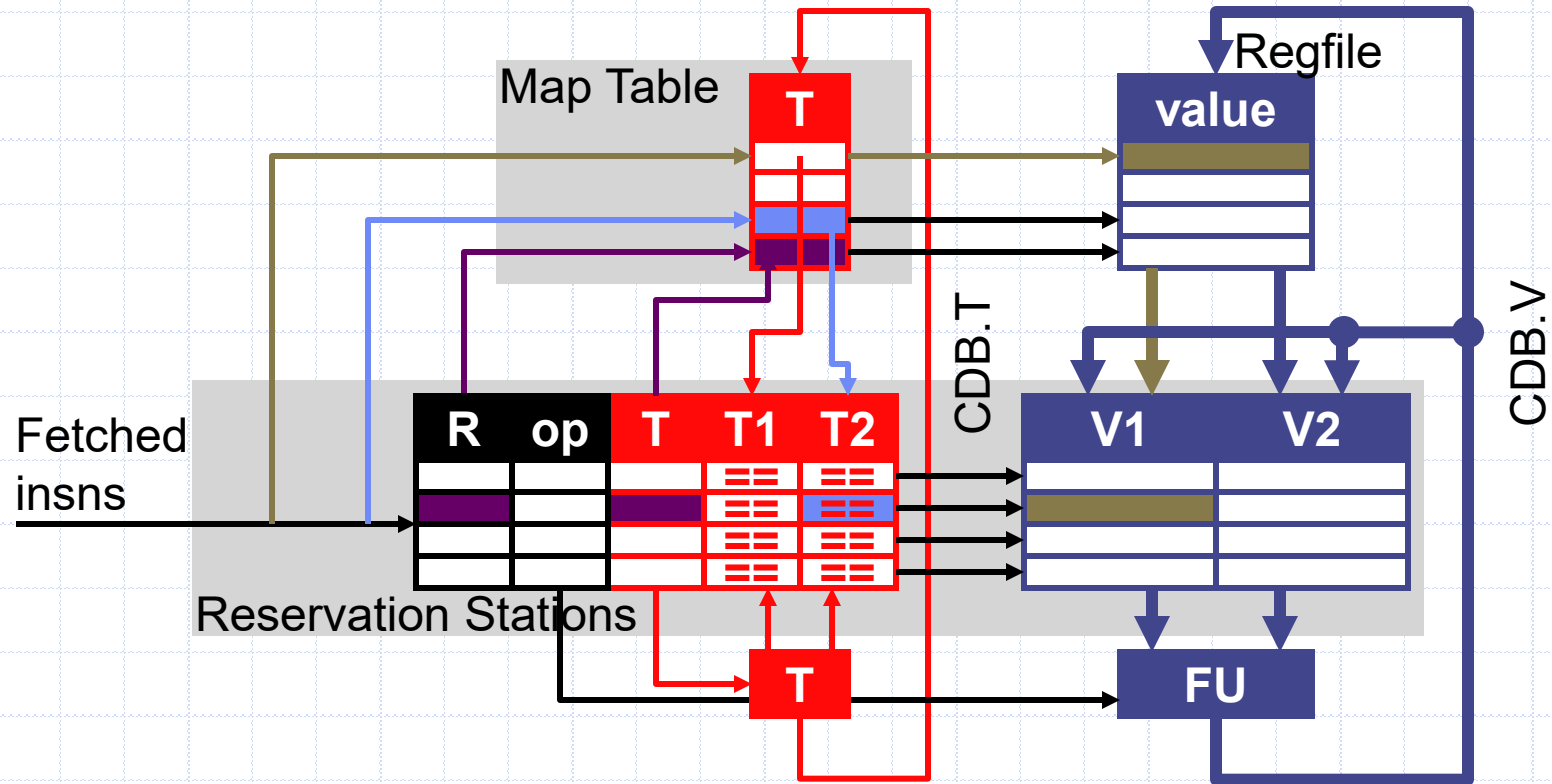
# Simple Tomasulo Pipeline

---

- New pipeline structure: F, **D**, **S**, X, **W**
  - **D (dispatch)**
    - **Structural** hazard ? **stall** : allocate RS entry
  - **S (issue)**
    - **RAW** hazard ? **wait** (monitor CDB) : go to execute
  - **W (writeback)**
    - Wait for CDB
    - **W**rite register, free RS entry
    - W and RAW-dependent S in same cycle
    - W and structural-dependent D in same cycle

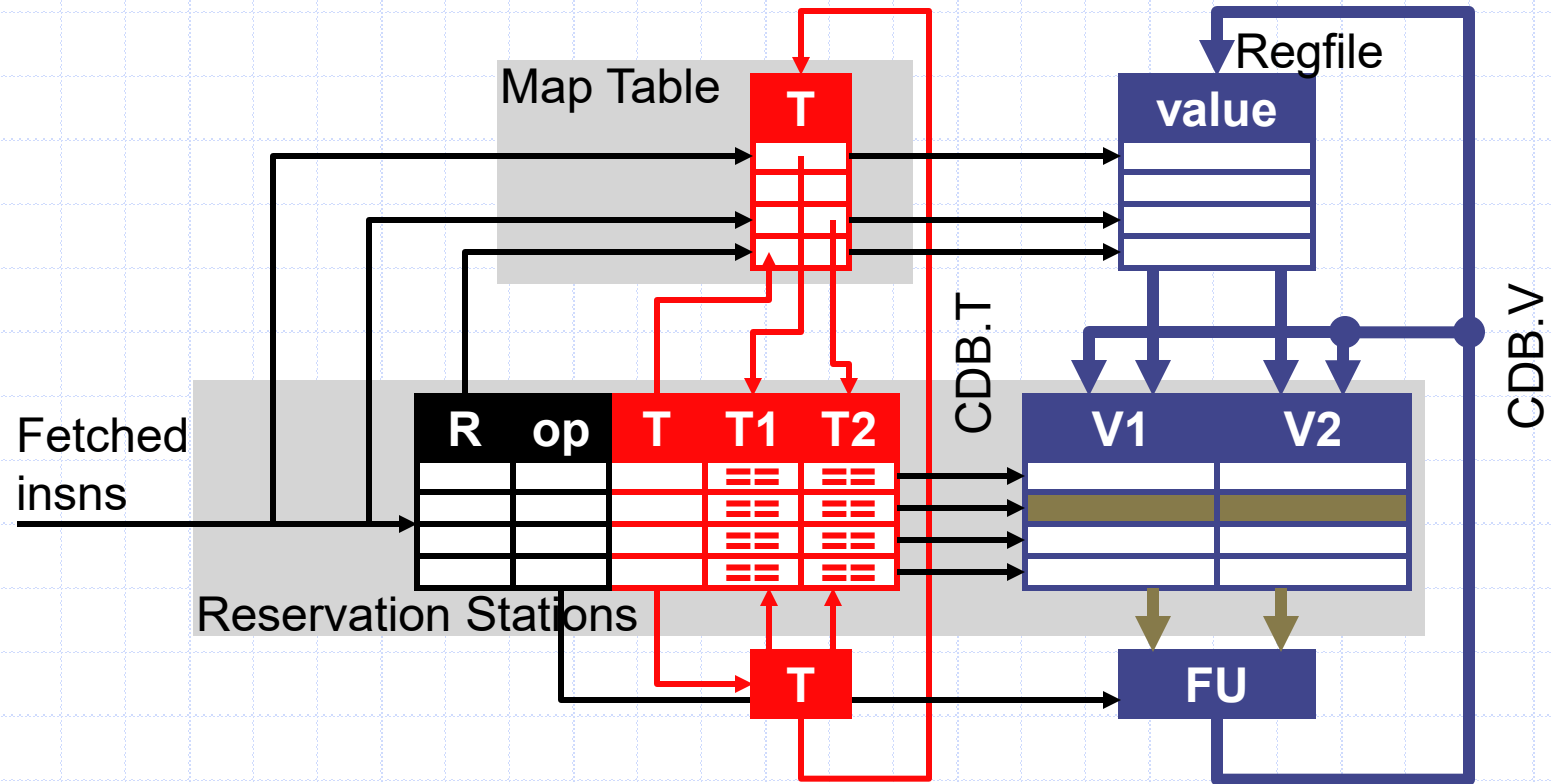


# Tomasulo Dispatch (D)



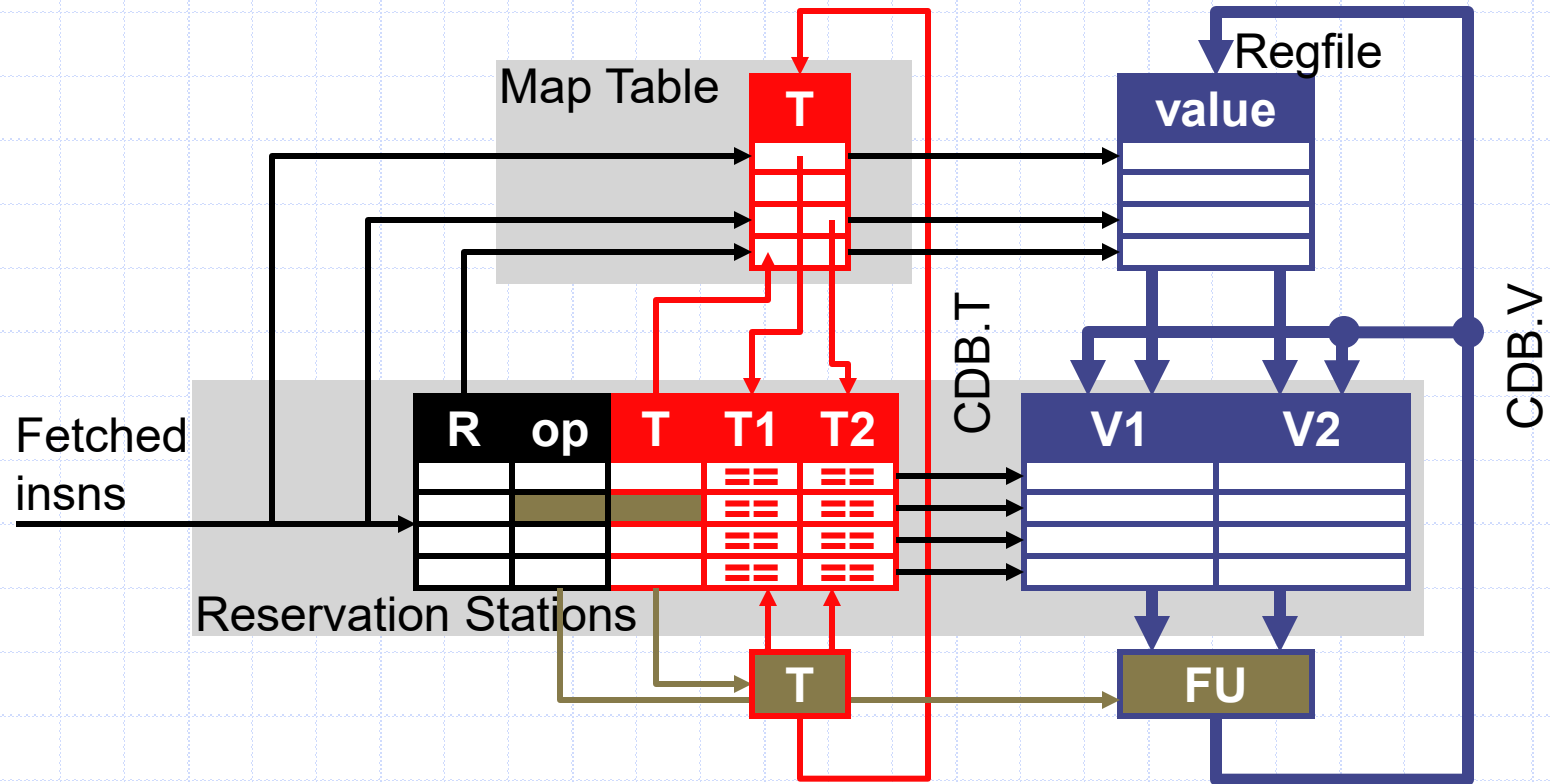
- Stall for structural (RS) hazards
  - Allocate RS entry
  - Input register ready ? read value into RS : read tag into RS
  - Set register status (i.e., rename) for output register

# Tomasulo Issue (S)

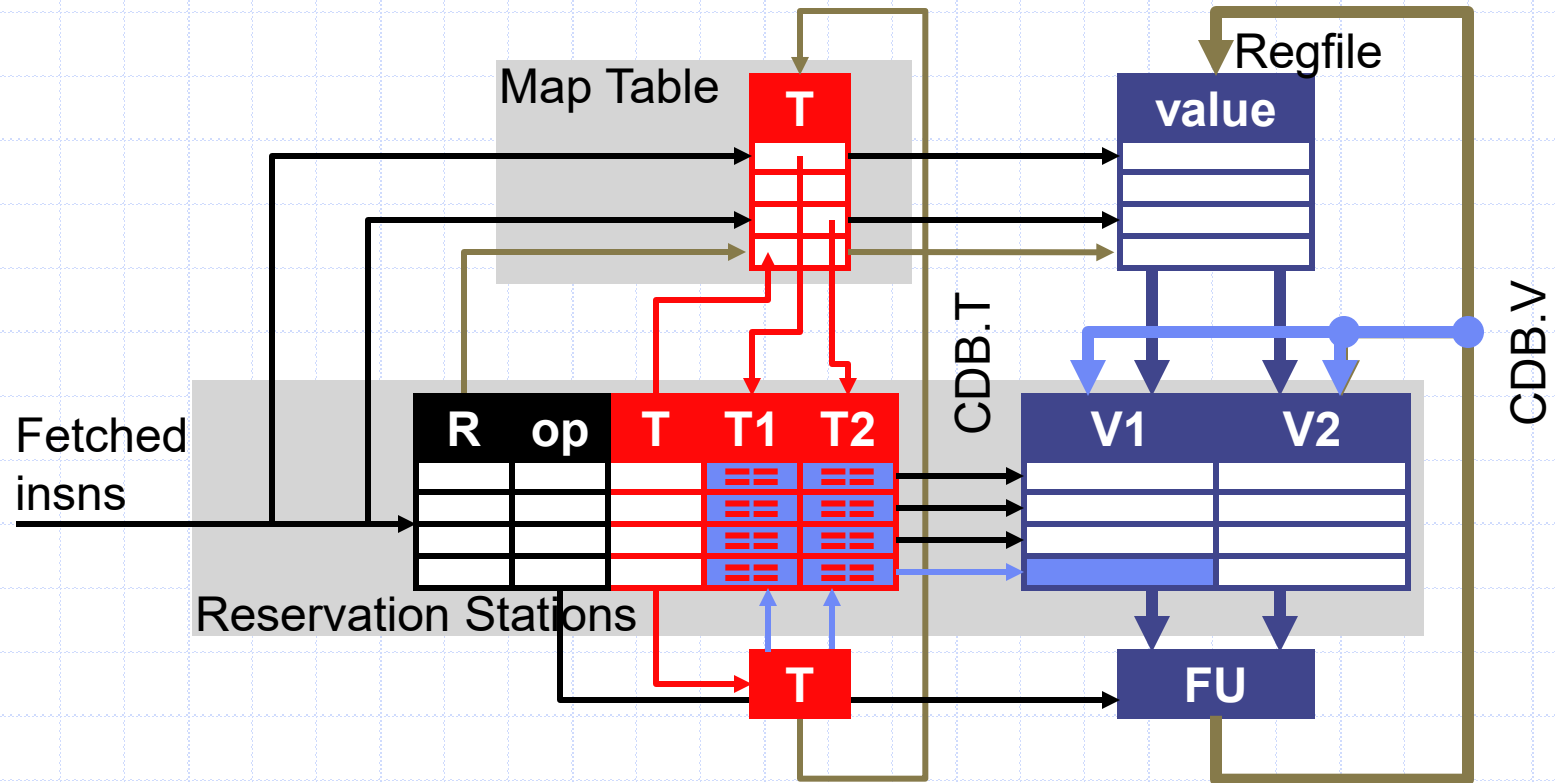


- Wait for RAW hazards
  - Read register values from RS

# Tomasulo Execute (X)

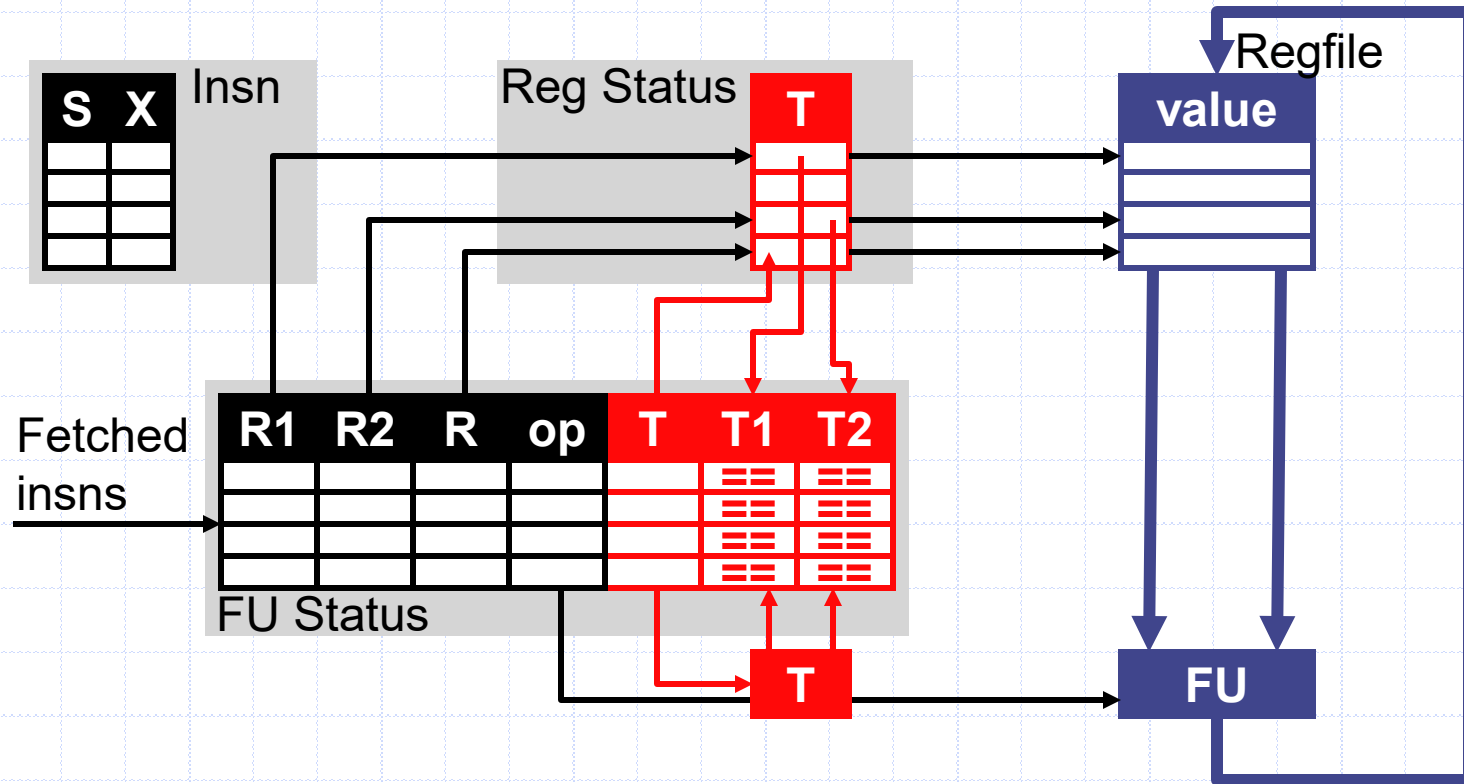


# Tomasulo Writeback (W)

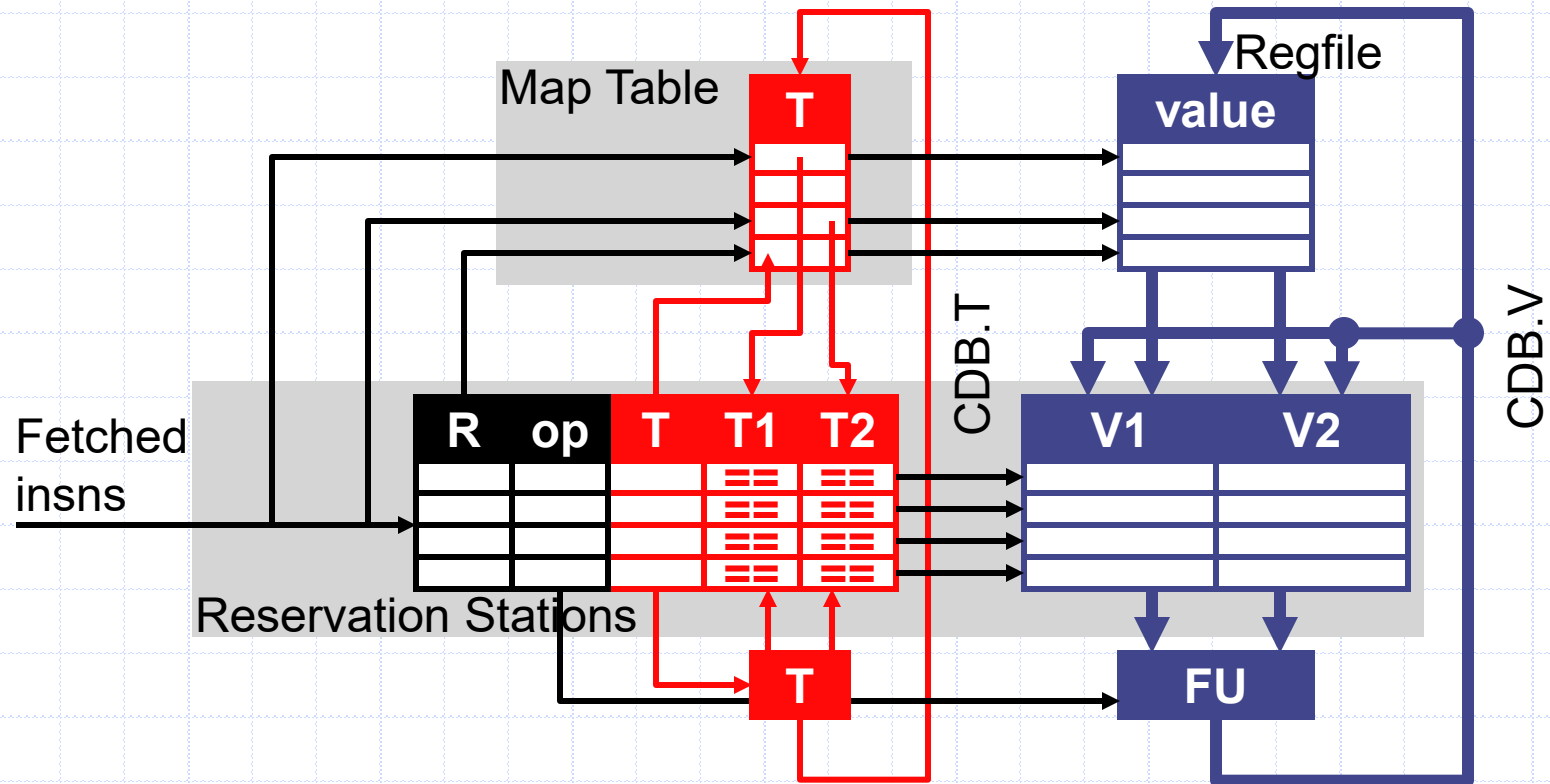


- Wait for structural (CDB) hazards
  - Output Reg Status tag still matches? clear, write result to register
  - CDB broadcast to RS: tag match ? clear tag, copy value
  - Free RS entry

# Difference Between Scoreboard...



# ...And Tomasulo



- What in Tomasulo implements **register renaming**?
  - **Value copies in RS (V1, V2)**
  - Insn stores correct input values in its own RS entry
  - + Future insns can overwrite master copy in regfile, doesn't matter

# Value/Copy-Based Register Renaming

---

- Tomasulo-style register renaming
  - Called “**value-based**” or “**copy-based**”
  - **Names:** architectural registers
  - **Storage locations:** register file and reservation stations
    - Values can and do exist in both
    - Register file holds master (i.e., most recent) values + RS copies eliminate WAR hazards
  - Storage locations referred to internally by RS# tags
    - Register table translates names to tags
    - Tag == 0 value is in register file
    - Tag != 0 value is not ready and is being computed by RS#
  - CDB broadcasts values with tags attached
    - So insns know what value they are looking at

# Value-Based Renaming Example

**ldf** **x(r1)** , **f1** (allocated RS#2)

- $MT[r1] == 0 \rightarrow RS[2].V2 = RF[r1]$
- $MT[f1] = RS\#2$

**mul****f** **f0** , **f1** , **f2** (allocate RS#4)

- $MT[f0] == 0 \rightarrow RS[4].V1 = RF[f0]$
- $MT[f1] == RS\#2 \rightarrow RS[4].T2 = RS\#2$
- $MT[f2] = RS\#4$

**add****f** **f7** , **f8** , **f0**

- Can write  $RF[f0]$  before **mul****f** executes, why?

**ldf** **x(r1)** , **f1**

- Can write  $RF[f1]$  before **mul****f** executes, why?
- Can write  $RF[f1]$  before first **ldf**, why?

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#4 |
| r1        |      |

| Reservation Stations |     |      |     |    |    |      |      |      |
|----------------------|-----|------|-----|----|----|------|------|------|
| T                    | FU  | busy | op  | R  | T1 | T2   | V1   | V2   |
| 2                    | LD  | yes  | ldf | f1 | -  | -    | -    | [r1] |
| 4                    | FP1 | yes  | mul | f2 | -  | RS#2 | [f0] |      |



# Tomasulo Data Structures

| Insn Status   |   |   |   |   |
|---------------|---|---|---|---|
| Insn          | D | S | X | W |
| ldf X(r1),f1  |   |   |   |   |
| mulf f0,f1,f2 |   |   |   |   |
| stf f2,Z(r1)  |   |   |   |   |
| addi r1,4,r1  |   |   |   |   |
| ldf X(r1),f1  |   |   |   |   |
| mulf f0,f1,f2 |   |   |   |   |
| stf f2,Z(r1)  |   |   |   |   |

| Map Table |   |
|-----------|---|
| Reg       | T |
| f0        |   |
| f1        |   |
| f2        |   |
| r1        |   |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

| Reservation Stations |     |      |    |   |    |    |    |    |
|----------------------|-----|------|----|---|----|----|----|----|
| T                    | FU  | busy | op | R | T1 | T2 | V1 | V2 |
| 1                    | ALU | no   |    |   |    |    |    |    |
| 2                    | LD  | no   |    |   |    |    |    |    |
| 3                    | ST  | no   |    |   |    |    |    |    |
| 4                    | FP1 | no   |    |   |    |    |    |    |
| 5                    | FP2 | no   |    |   |    |    |    |    |

# Tomasulo: Cycle 1

| Insn Status     |    |   |   |   |
|-----------------|----|---|---|---|
| Insn            | D  | S | X | W |
| ldf X(r1), f1   | c1 |   |   |   |
| mulf f0, f1, f2 |    |   |   |   |
| stf f2, Z(r1)   |    |   |   |   |
| addi r1, 4, r1  |    |   |   |   |
| ldf X(r1), f1   |    |   |   |   |
| mulf f0, f1, f2 |    |   |   |   |
| stf f2, Z(r1)   |    |   |   |   |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        |      |
| r1        |      |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

| Reservation Stations |     |      |     |    |    |    |    |      |
|----------------------|-----|------|-----|----|----|----|----|------|
| T                    | FU  | busy | op  | R  | T1 | T2 | V1 | V2   |
| 1                    | ALU | no   |     |    |    |    |    |      |
| 2                    | LD  | yes  | ldf | f1 | -  | -  | -  | [r1] |
| 3                    | ST  | no   |     |    |    |    |    |      |
| 4                    | FP1 | no   |     |    |    |    |    |      |
| 5                    | FP2 | no   |     |    |    |    |    |      |

allocate

# Tomasulo: Cycle 2

| Insn Status     |    |    |   |   |
|-----------------|----|----|---|---|
| Insn            | D  | S  | X | W |
| ldf X(r1), f1   | c1 | c2 |   |   |
| mulf f0, f1, f2 | c2 |    |   |   |
| stf f2, Z(r1)   |    |    |   |   |
| addi r1, 4, r1  |    |    |   |   |
| ldf X(r1), f1   |    |    |   |   |
| mulf f0, f1, f2 |    |    |   |   |
| stf f2, Z(r1)   |    |    |   |   |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#4 |
| r1        |      |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

| Reservation Stations |     |      |      |    |    |      |      |      |
|----------------------|-----|------|------|----|----|------|------|------|
| T                    | FU  | busy | op   | R  | T1 | T2   | V1   | V2   |
| 1                    | ALU | no   |      |    |    |      |      |      |
| 2                    | LD  | yes  | ldf  | f1 | -  | -    | -    | [r1] |
| 3                    | ST  | no   |      |    |    |      |      |      |
| 4                    | FP1 | yes  | mulf | f2 | -  | RS#2 | [f0] | -    |
| 5                    | FP2 | no   |      |    |    |      |      |      |

allocate

# Tomasulo: Cycle 3

| Insn Status     |    |    |    |   |
|-----------------|----|----|----|---|
| Insn            | D  | S  | X  | W |
| ldf X(r1), f1   | c1 | c2 | c3 |   |
| mulf f0, f1, f2 | c2 |    |    |   |
| stf f2, Z(r1)   | c3 |    |    |   |
| addi r1, 4, r1  |    |    |    |   |
| ldf X(r1), f1   |    |    |    |   |
| mulf f0, f1, f2 |    |    |    |   |
| stf f2, Z(r1)   |    |    |    |   |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#4 |
| r1        |      |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

| Reservation Stations |     |      |      |    |      |      |      |      |
|----------------------|-----|------|------|----|------|------|------|------|
| T                    | FU  | busy | op   | R  | T1   | T2   | V1   | V2   |
| 1                    | ALU | no   |      |    |      |      |      |      |
| 2                    | LD  | yes  | ldf  | f1 | -    | -    | -    | [r1] |
| 3                    | ST  | yes  | stf  | -  | RS#4 | -    | -    | [r1] |
| 4                    | FP1 | yes  | mulf | f2 | -    | RS#2 | [f0] | -    |
| 5                    | FP2 | no   |      |    |      |      |      |      |

allocate

# Tomasulo: Cycle 4

| Insn Status     |           |           |    |           |
|-----------------|-----------|-----------|----|-----------|
| Insn            | D         | S         | X  | W         |
| ldf X(r1), f1   | c1        | c2        | c3 | <b>c4</b> |
| mulf f0, f1, f2 | c2        | <b>c4</b> |    |           |
| stf f2, Z(r1)   | c3        |           |    |           |
| addi r1, 4, r1  | <b>c4</b> |           |    |           |
| ldf X(r1), f1   |           |           |    |           |
| mulf f0, f1, f2 |           |           |    |           |
| stf f2, Z(r1)   |           |           |    |           |

| Map Table |             |
|-----------|-------------|
| Reg       | T           |
| f0        |             |
| f1        | <u>RS#2</u> |
| f2        | RS#4        |
| r1        | RS#1        |

| CDB         |             |
|-------------|-------------|
| T           | V           |
| <b>RS#2</b> | <b>[f1]</b> |

| Reservation Stations |            |            |             |           |      |             |             |              |
|----------------------|------------|------------|-------------|-----------|------|-------------|-------------|--------------|
| T                    | FU         | busy       | op          | R         | T1   | T2          | V1          | V2           |
| <b>1</b>             | <b>ALU</b> | <b>yes</b> | <b>addi</b> | <b>r1</b> | -    | -           | <b>[r1]</b> | -            |
| <b>2</b>             | <b>LD</b>  | <b>no</b>  |             |           |      |             |             |              |
| 3                    | ST         | yes        | stf         | -         | RS#4 | -           | -           | [r1]         |
| 4                    | FP1        | yes        | mulf        | f2        | -    | <u>RS#2</u> | [f0]        | <u>CDB.V</u> |
| 5                    | FP2        | no         |             |           |      |             |             |              |

ldf finished (W)  
clear f1 RegStatus  
CDB broadcast

allocate  
free

RS#2 ready →  
grab CDB value

# Tomasulo: Cycle 5

| Insn Status     |    |    |    |    |
|-----------------|----|----|----|----|
| Insn            | D  | S  | X  | W  |
| ldf X(r1), f1   | c1 | c2 | c3 | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5 |    |
| stf f2, Z(r1)   | c3 |    |    |    |
| addi r1, 4, r1  | c4 | c5 |    |    |
| ldf X(r1), f1   | c5 |    |    |    |
| mulf f0, f1, f2 |    |    |    |    |
| stf f2, Z(r1)   |    |    |    |    |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#4 |
| r1        | RS#1 |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

| Reservation Stations |     |      |      |    |      |      |      |      |
|----------------------|-----|------|------|----|------|------|------|------|
| T                    | FU  | busy | op   | R  | T1   | T2   | V1   | V2   |
| 1                    | ALU | yes  | addi | r1 | -    | -    | [r1] | -    |
| 2                    | LD  | yes  | ldf  | f1 | -    | RS#1 | -    | -    |
| 3                    | ST  | yes  | stf  | -  | RS#4 | -    | -    | [r1] |
| 4                    | FP1 | yes  | mulf | f2 | -    | -    | [f0] | [f1] |
| 5                    | FP2 | no   |      |    |      |      |      |      |

allocate

# Tomasulo: Cycle 6

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ |    |
| stf f2, Z(r1)   | c3 |    |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  |    |
| ldf X(r1), f1   | c5 |    |     |    |
| mulf f0, f1, f2 | c6 |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Map Table |           |
|-----------|-----------|
| Reg       | T         |
| f0        |           |
| f1        | RS#2      |
| f2        | RS#4 RS#5 |
| r1        | RS#1      |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

no D stall on WAW: scoreboard would  
overwrite f2 RegStatus —  
anyone who needs old f2 tag has it

| Reservation Stations |     |      |      |    |      |      |      |      |
|----------------------|-----|------|------|----|------|------|------|------|
| T                    | FU  | busy | op   | R  | T1   | T2   | V1   | V2   |
| 1                    | ALU | yes  | addi | r1 | -    | -    | [r1] | -    |
| 2                    | LD  | yes  | ldf  | f1 | -    | RS#1 | -    | -    |
| 3                    | ST  | yes  | stf  | -  | RS#4 | -    | -    | [r1] |
| 4                    | FP1 | yes  | mulf | f2 | -    | -    | [f0] | [f1] |
| 5                    | FP2 | yes  | mulf | f2 | -    | RS#2 | [f0] | -    |

allocate

# Tomasulo: Cycle 7

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ |    |
| stf f2, Z(r1)   | c3 |    |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  | c7 |
| ldf X(r1), f1   | c5 | c7 |     |    |
| mulf f0, f1, f2 | c6 |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Map Table |             |
|-----------|-------------|
| Reg       | T           |
| f0        |             |
| f1        | RS#2        |
| f2        | RS#5        |
| r1        | <u>RS#1</u> |

| CDB  |      |
|------|------|
| T    | V    |
| RS#1 | [r1] |

no W wait on WAR: scoreboard would  
 anyone who needs old r1 has RS copy  
 D stall on store RS: structural

| Reservation Stations |     |      |      |    |      |             |      |              |
|----------------------|-----|------|------|----|------|-------------|------|--------------|
| T                    | FU  | busy | op   | R  | T1   | T2          | V1   | V2           |
| 1                    | ALU | no   |      |    |      |             |      |              |
| 2                    | LD  | yes  | ldf  | f1 | -    | <u>RS#1</u> | -    | <u>CDB.V</u> |
| 3                    | ST  | yes  | stf  | -  | RS#4 | -           | -    | [r1]         |
| 4                    | FP1 | yes  | mulf | f2 | -    | -           | [f0] | [f1]         |
| 5                    | FP2 | yes  | mulf | f2 | -    | RS#2        | [f0] | -            |

addi finished (W)  
 clear r1 RegStatus  
 CDB broadcast

RS#1 ready →  
 grab CDB value



# Tomasulo: Cycle 8

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ | c8 |
| stf f2, Z(r1)   | c3 | c8 |     |    |
| addi r1, 4, r1  | c4 | c5 | c6  | c7 |
| ldf X(r1), f1   | c5 | c7 | c8  |    |
| mulf f0, f1, f2 | c6 |    |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#5 |
| r1        |      |

| CDB  |      |
|------|------|
| T    | V    |
| RS#4 | [f2] |

**mulf finished (W)**  
**don't clear f2 RegStatus**  
**already overwritten by 2nd mulf (RS#5)**  
**CDB broadcast**

| Reservation Stations |     |      |      |    |      |      |       |      |
|----------------------|-----|------|------|----|------|------|-------|------|
| T                    | FU  | busy | op   | R  | T1   | T2   | V1    | V2   |
| 1                    | ALU | no   |      |    |      |      |       |      |
| 2                    | LD  | yes  | ldf  | f1 | -    | -    | -     | [r1] |
| 3                    | ST  | yes  | stf  | -  | RS#4 | -    | CDB.V | [r1] |
| 4                    | FP1 | no   |      |    |      |      |       |      |
| 5                    | FP2 | yes  | mulf | f2 | -    | RS#2 | [f0]  | -    |

**RS#4 ready →**  
**grab CDB value**

# Tomasulo: Cycle 9

| Insn Status     |    |    |     |    |
|-----------------|----|----|-----|----|
| Insn            | D  | S  | X   | W  |
| ldf X(r1), f1   | c1 | c2 | c3  | c4 |
| mulf f0, f1, f2 | c2 | c4 | c5+ | c8 |
| stf f2, Z(r1)   | c3 | c8 | c9  |    |
| addi r1, 4, r1  | c4 | c5 | c6  | c7 |
| ldf X(r1), f1   | c5 | c7 | c8  | c9 |
| mulf f0, f1, f2 | c6 | c9 |     |    |
| stf f2, Z(r1)   |    |    |     |    |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        | RS#2 |
| f2        | RS#5 |
| r1        |      |

| CDB  |      |
|------|------|
| T    | V    |
| RS#2 | [f1] |

2nd ldf finished (W)  
clear f1 RegStatus  
CDB broadcast

| Reservation Stations |     |      |      |    |    |      |      |       |
|----------------------|-----|------|------|----|----|------|------|-------|
| T                    | FU  | busy | op   | R  | T1 | T2   | V1   | V2    |
| 1                    | ALU | no   |      |    |    |      |      |       |
| 2                    | LD  | no   |      |    |    |      |      |       |
| 3                    | ST  | yes  | stf  | -  | -  | -    | [f2] | [r1]  |
| 4                    | FP1 | no   |      |    |    |      |      |       |
| 5                    | FP2 | yes  | mulf | f2 | -  | RS#2 | [f0] | CDB.V |

RS#2 ready →  
grab CDB value

# Tomasulo: Cycle 10

| Insn Status     |     |    |     |     |
|-----------------|-----|----|-----|-----|
| Insn            | D   | S  | X   | W   |
| ldf X(r1), f1   | c1  | c2 | c3  | c4  |
| mulf f0, f1, f2 | c2  | c4 | c5+ | c8  |
| stf f2, Z(r1)   | c3  | c8 | c9  | c10 |
| addi r1, 4, r1  | c4  | c5 | c6  | c7  |
| ldf X(r1), f1   | c5  | c7 | c8  | c9  |
| mulf f0, f1, f2 | c6  | c9 | c10 |     |
| stf f2, Z(r1)   | c10 |    |     |     |

| Map Table |      |
|-----------|------|
| Reg       | T    |
| f0        |      |
| f1        |      |
| f2        | RS#5 |
| r1        |      |

| CDB |   |
|-----|---|
| T   | V |
|     |   |

**stf finished (W)**  
**no output register → no CDB broadcast**

| Reservation Stations |     |      |      |    |      |    |      |      |
|----------------------|-----|------|------|----|------|----|------|------|
| T                    | FU  | busy | op   | R  | T1   | T2 | V1   | V2   |
| 1                    | ALU | no   |      |    |      |    |      |      |
| 2                    | LD  | no   |      |    |      |    |      |      |
| 3                    | ST  | yes  | stf  | -  | RS#5 | -  | -    | [r1] |
| 4                    | FP1 | no   |      |    |      |    |      |      |
| 5                    | FP2 | yes  | mulf | f2 | -    | -  | [f0] | [f1] |

**free → allocate**

# Scoreboard vs. Tomasulo

|               | Scoreboard |     |      |     | Tomasulo |     |      |     |
|---------------|------------|-----|------|-----|----------|-----|------|-----|
| Insn          | D          | S   | X    | W   | D        | S   | X    | W   |
| ldf X(r1),f1  | c1         | c2  | c3   | c4  | c1       | c2  | c3   | c4  |
| mulf f0,f1,f2 | c2         | c4  | c5+  | c8  | c2       | c4  | c5+  | c8  |
| stf f2,Z(r1)  | c3         | c8  | c9   | c10 | c3       | c8  | c9   | c10 |
| addi r1,4,r1  | c4         | c5  | c6   | c9  | c4       | c5  | c6   | c7  |
| ldf X(r1),f1  | c5         | c9  | c10  | c11 | c5       | c7  | c8   | c9  |
| mulf f0,f1,f2 | c8         | c11 | c12+ | c15 | c6       | c9  | c10+ | c13 |
| stf f2,Z(r1)  | c10        | c15 | c16  | c17 | c10      | c13 | c14  | c15 |

| Hazard      | Scoreboard | Tomasulo   |
|-------------|------------|------------|
| Insn buffer | stall in D | stall in D |
| FU          | wait in S  | wait in S  |
| RAW         | wait in S  | wait in S  |
| WAR         | wait in W  | none       |
| WAW         | stall in D | none       |

# Scoreboard vs. Tomasulo II: Cache Miss

|               | Scoreboard |     |      |     | Tomasulo |     |      |     |
|---------------|------------|-----|------|-----|----------|-----|------|-----|
| Insn          | D          | S   | X    | W   | D        | S   | X    | W   |
| ldf X(r1),f1  | c1         | c2  | c3+  | c8  | c1       | c2  | c3+  | c8  |
| mulf f0,f1,f2 | c2         | c8  | c9+  | c12 | c2       | c8  | c9+  | c12 |
| stf f2,Z(r1)  | c3         | c12 | c13  | c14 | c3       | c12 | c13  | c14 |
| addi r1,4,r1  | c4         | c5  | c6   | c13 | c4       | c5  | c6   | c7  |
| ldf X(r1),f1  | c8         | c13 | c14  | c15 | c5       | c7  | c8   | c9  |
| mulf f0,f1,f2 | c12        | c15 | c16+ | c19 | c6       | c9  | c10+ | c13 |
| stf f2,Z(r1)  | c13        | c19 | c20  | c21 | c7       | c13 | c14  | c15 |

- Assume
  - 5 cycle cache miss on first `ldf`
  - Ignore FUST and RS structural hazards
- + Advantage Tomasulo
  - No `addi` **WAR hazard** (c7) means iterations run in parallel

# Can We Add Superscalar?

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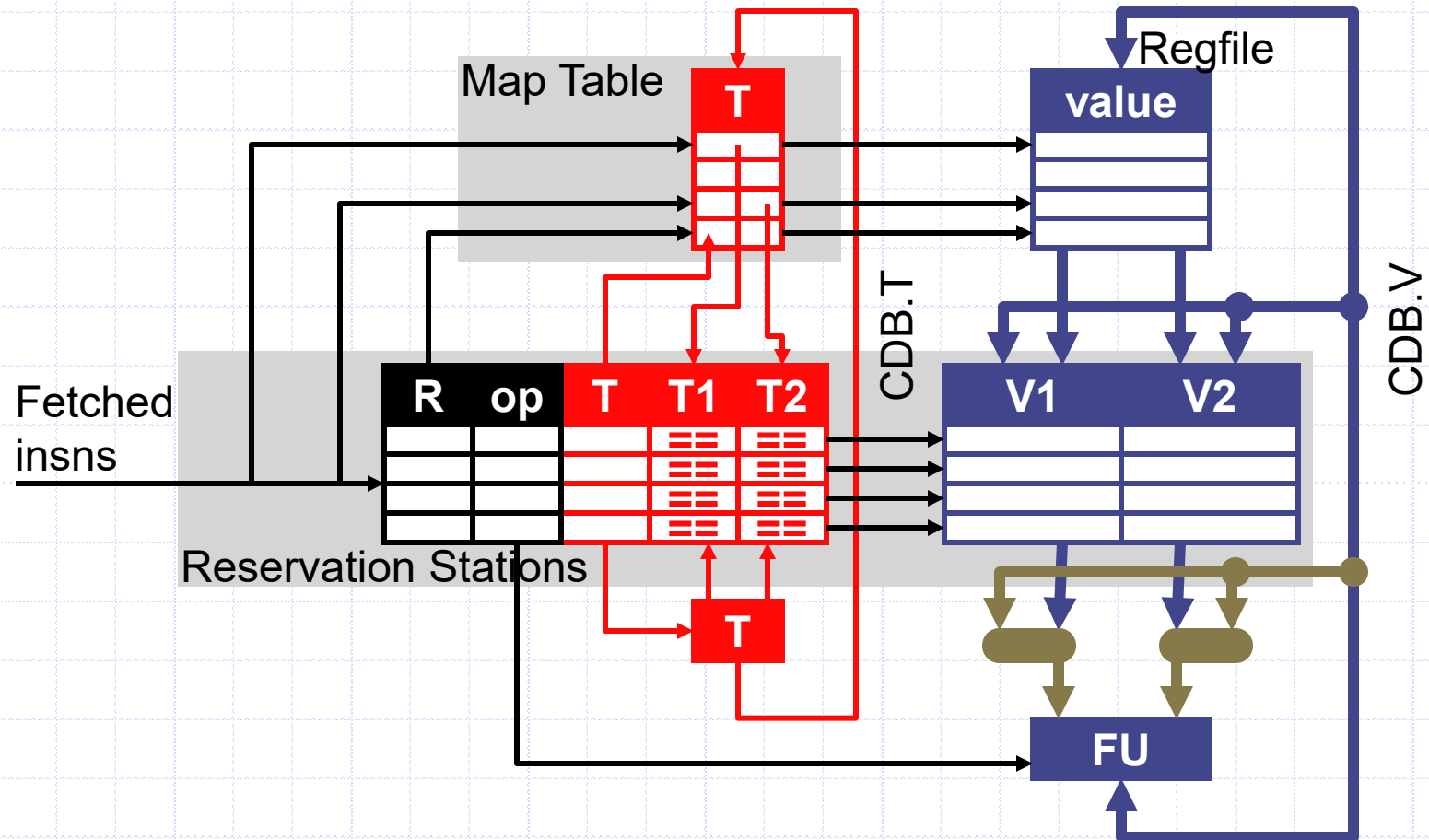
- Dynamic scheduling and multiple issue are orthogonal
  - E.g., Pentium4: dynamically scheduled 5-way superscalar
  - Two dimensions
    - **N**: superscalar width (number of parallel operations)
    - **W**: window size (number of reservation stations)
- What do we need for an **N**-by-**W** Tomasulo?
  - RS: **N** tag/value w-ports (D), **N** value r-ports (S), **2N** tag CAMs (W)
  - Select logic: **W**→**N** priority encoder (S)
  - MT: **2N** r-ports (D), **N** w-ports (D)
  - RF: **2N** r-ports (D), **N** w-ports (W)
  - CDB: **N** (W)
  - Which are the expensive pieces?

# Superscalar Select Logic

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- Superscalar select logic:  $W \rightarrow N$  priority encoder
  - Somewhat complicated ( $N^2 \log W$ )
  - Can simplify using different RS designs
- **Split design**
  - Divide RS into  $N$  banks: 1 per FU?
  - Implement  $N$  separate  $W/N \rightarrow 1$  encoders
  - + Simpler:  $N * \log W/N$
  - Less scheduling flexibility
- **FIFO design** [Palacharla+]
  - Can issue only head of each RS bank
  - + Simpler: no select logic at all
  - Less scheduling flexibility (but surprisingly not that bad)

# Can We Add Bypassing?



- Yes, but it's more complicated than you might think
  - In fact: requires a completely new pipeline



# Why Out-of-Order Bypassing Is Hard

| Insn           | No Bypassing |     |      |     | Bypassing |     |     |     |
|----------------|--------------|-----|------|-----|-----------|-----|-----|-----|
|                | D            | S   | X    | W   | D         | S   | X   | W   |
| ldf X(r1), f1  | c1           | c2  | c3   | c4  | c1        | c2  | c3  | c4  |
| mul f0, f1, f2 | c2           | c4  | c5+  | c8  | c2        | c3  | c4+ | c7  |
| stf f2, Z(r1)  | c3           | c8  | c9   | c10 | c3        | c6  | c7  | c8  |
| addi r1, 4, r1 | c4           | c5  | c6   | c7  | c4        | c5  | c6  | c7  |
| ldf X(r1), f1  | c5           | c7  | c8   | c9  | c5        | c7  | c7  | c9  |
| mul f0, f1, f2 | c6           | c9  | c10+ | c13 | c6        | c9  | c8+ | c13 |
| stf f2, Z(r1)  | c10          | c13 | c14  | c15 | c10       | c13 | c11 | c15 |

- Bypassing: **ldf** X in c3 → **mul** X in c4 → **mul** S in c3
  - But how can **mul** S in c3 if **ldf** W in c4? Must change pipeline
- Modern scheduler
  - Split CDB tag and value, move tag broadcast to S
    - **ldf** tag broadcast now in cycle 2 → **mul** S in cycle 3
  - How do multi-cycle operations work? How do cache misses work?

# Dynamic Scheduling Summary

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- Dynamic scheduling: out-of-order execution
  - Higher pipeline/FU utilization, improved performance
  - Easier and more effective in hardware than software
    - + More storage locations than architectural registers
    - + Dynamic handling of cache misses
- Instruction buffer: multiple F/D latches
  - Implements large scheduling scope + “passing” functionality
  - Split decode into in-order dispatch and out-of-order issue
    - Stall vs. wait
- Dynamic scheduling algorithms
  - Scoreboard: no register renaming, limited out-of-order
  - Tomasulo: copy-based register renaming, full out-of-order