

Tomasulo Loop Example

```
Loop:  LD          F0      0      R1
        MULTD     F4      F0     F2
        SD        F4      0      R1
        SUBI      R1      R1     #8
        BNEZ     R1      Loop
```

- This time assume Multiply takes 4 clocks
- Assume 1st load takes 8 clocks, 2nd load takes 1 clock
- Clocks for SUBI , BNEZ
- Show 2 iterations

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | | | Load1 | No | |
| 1 | MULTD | F4 | F0 | F2 | | Load2 | No | | |
| 1 | SD | F4 | 0 | R1 | | Load3 | No | | |
| 2 | LD | F0 | 0 | R1 | | Store1 | No | | |
| 2 | MULTD | F4 | F0 | F2 | | Store2 | No | | |
| 2 | SD | F4 | 0 | R1 | | Store3 | No | | |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> | | | |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|--------------|----|------|----|
| | Add1 | No | | | | | | LD | F0 | 0 | R1 |
| | Add2 | No | | | | | | MULTD | F4 | F0 | F2 |
| | Add3 | No | | | | | | SD | F4 | 0 | R1 |
| | Mult1 | No | | | | | | SUBI | R1 | R1 | #8 |
| | Mult2 | No | | | | | | BNEZ | R1 | Loop | |

Register result status

| <i>Clock</i> | <i>R1</i> | | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 0 | 80 | <i>Fu</i> | | | | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| | | | | | | Load2 | No | |
| | | | | | | Load3 | No | |
| | | | | | | Store1 | No | |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|----------------|
| | Add1 | No | | | | | | LD F0 0 R1 ← |
| | Add2 | No | | | | | | MULTD F4 F0 F2 |
| | Add3 | No | | | | | | SD F4 0 R1 |
| | Mult1 | No | | | | | | SUBI R1 R1 #8 |
| | Mult2 | No | | | | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 1 | 80 | <i>Fu</i> | Load1 | | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | No | |
| | | | | | | Load3 | No | |
| | | | | | | Store1 | No | |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

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

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 2 | 80 | <i>Fu</i> | Load1 | Mult1 | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| | | | | | | Store1 | Yes 80 | Mult1 |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

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

Register result status

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

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| | | | | | | Store1 | Yes 80 | Mult1 |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

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

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 4 | 80 | <i>Fu</i> | Load1 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| | | | | | | Store1 | Yes 80 | Mult1 |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

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

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 5 | 72 | <i>Fu</i> | Load1 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | Yes 72 | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| 2 | LD | F0 | 0 | R1 | 6 | Store1 | Yes 80 | Mult1 |
| | | | | | | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

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

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 6 | 72 | <i>Fu</i> | Load2 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | Yes 72 | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| 2 | LD | F0 | 0 | R1 | 6 | Store1 | Yes 80 | Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | Store2 | No | |
| | | | | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| | Mult1 | Yes | Multd | | R(F2) | Load1 | | SUBI R1 R1 #8 |
| | Mult2 | Yes | Multd | | R(F2) | Load2 | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 7 | 72 | <i>Fu</i> | Load2 | | Mult2 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | Load1 | Yes 80 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | Load2 | Yes 72 | |
| 1 | SD | F4 | 0 | R1 | 3 | Load3 | No | |
| 2 | LD | F0 | 0 | R1 | 6 | Store1 | Yes 80 | Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | Store2 | Yes 72 | Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | Store3 | No | |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|----------------|
| Add1 | No | | | | | | | LD F0 0 R1 |
| Add2 | No | | | | | | | MULTD F4 F0 F2 |
| Add3 | No | | | | | | | SD F4 0 R1 ← |
| Mult1 | Yes | Multd | | R(F2) | Load1 | | | SUBI R1 R1 #8 |
| Mult2 | Yes | Multd | | R(F2) | Load2 | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 8 | 72 | <i>Fu</i> | Load2 | Mult2 | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>CompResult</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | Load1 | Yes 80 |
| 1 | MULTD | F4 | F0 | F2 | 2 | | Load2 | Yes 72 |
| 1 | SD | F4 | 0 | R1 | 3 | | Load3 | No |
| 2 | LD | F0 | 0 | R1 | 6 | | Store1 | Yes 80 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | Store2 | Yes 72 |
| 2 | SD | F4 | 0 | R1 | 8 | | Store3 | No |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 |
| | Add3 | No | | | | | | SD F4 0 R1 |
| | Mult1 | Yes | Multd | | R(F2) | Load1 | | SUBI R1 R1 #8 ← |
| | Mult2 | Yes | Multd | | R(F2) | Load2 | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 9 | 72 | <i>Fu</i> | Load2 | | Mult2 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue CompResult</i> | | | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|-------------------------|---|----|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | | | Load2 | Yes 72 |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | No |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | | Store1 | Yes 80 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | | Store2 | Yes 72 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> | | | |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|--------------|----|------|----|
| | Add1 | No | | | | | | LD | F0 | 0 | R1 |
| | Add2 | No | | | | | | MULTD | F4 | F0 | F2 |
| | Add3 | No | | | | | | SD | F4 | 0 | R1 |
| 4 | Mult1 | Yes | Multd | M[80] | R(F2) | | | SUBI | R1 | R1 | #8 |
| | Mult2 | Yes | Multd | | R(F2) | Load2 | | BNEZ | R1 | Loop | ← |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 10 | 64 | <i>Fu</i> | Load2 | | Mult2 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue CompResult</i> | | | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|-------------------------|---|----|-------------|-------------|--------------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | | | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | | Store2 | Yes 72 Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|----------------|
| | Add1 | No | | | | | | LD F0 0 R1 ← |
| | Add2 | No | | | | | | MULTD F4 F0 F2 |
| | Add3 | No | | | | | | SD F4 0 R1 |
| 3 | Mult1 | Yes | Multd | M[80] | R(F2) | | | SUBI R1 R1 #8 |
| 4 | Mult2 | Yes | Multd | M[72] | R(F2) | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 11 | 64 | <i>Fu</i> | Load3 | | | Mult2 | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue CompResult</i> | | | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> | |
|-------------|--------------------|----------|----------|-------------------------|---|----|-------------|-------------|-----------|-------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No | |
| 1 | MULTD | F4 | F0 | F2 | 2 | | | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 | |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 | Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | | Store2 | Yes 72 | Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No | |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| 2 | Mult1 | Yes | Multd | M[80] | R(F2) | | | SUBI R1 R1 #8 |
| 3 | Mult2 | Yes | Multd | M[72] | R(F2) | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 12 | 64 | <i>Fu</i> | Load3 | Mult2 | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue CompResult</i> | | | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> | |
|-------------|--------------------|----------|----------|-------------------------|---|----|-------------|-------------|-----------|-------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No | |
| 1 | MULTD | F4 | F0 | F2 | 2 | | | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 | |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 | Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | | Store2 | Yes 72 | Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No | |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| 1 | Mult1 | Yes | Multd | M[80] | R(F2) | | | SUBI R1 R1 #8 |
| 2 | Mult2 | Yes | Multd | M[72] | R(F2) | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 13 | 64 | <i>Fu</i> | Load3 | | Mult2 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue CompResult</i> | | | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> | |
|-------------|--------------------|----------|----------|-------------------------|---|----|-------------|-------------|-----------|-------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No | |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | | Load2 | No | |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 | |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 | Mult1 |
| 2 | MULTD | F4 | F0 | F2 | 7 | | | Store2 | Yes 72 | Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No | |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| 0 | Mult1 | Yes | Multd | M[80] | R(F2) | | | SUBI R1 R1 #8 |
| 1 | Mult2 | Yes | Multd | M[72] | R(F2) | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 14 | 64 | <i>Fu</i> | Load3 | | | Mult2 | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|----------------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 [80]*R2 |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | | Store2 | Yes 72 Mult2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| | Mult1 | No | | | | | | SUBI R1 R1 #8 |
| 0 | Mult2 | Yes | Multd | M[72] | R(F2) | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 15 | 64 | <i>Fu</i> | Load3 | Mult2 | | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|----------------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 [80]*R2 |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | 16 | Store2 | Yes 72 [72]*R2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | No |

Reservation Stations:

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|------------------|
| | Add1 | No | | | | | | LD F0 0 R1 |
| | Add2 | No | | | | | | MULTD F4 F0 F2 ← |
| | Add3 | No | | | | | | SD F4 0 R1 |
| 4 | Mult1 | Yes | Multd | | R(F2) | Load3 | | SUBI R1 R1 #8 |
| | Mult2 | No | | | | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 16 | 64 | <i>Fu</i> | Load3 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|----------------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | | | Load3 | Yes 64 |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 [80]*R2 |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | 16 | Store2 | Yes 72 [72]*R2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | Yes 64 Mult1 |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|----------------|
| Add1 | No | | | | | | | LD F0 0 R1 |
| Add2 | No | | | | | | | MULTD F4 F0 F2 |
| Add3 | No | | | | | | | SD F4 0 R1 ← |
| Mult1 | Yes | Multd | | | R(F2) | Load3 | | SUBI R1 R1 #8 |
| Mult2 | No | | | | | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 17 | 64 | <i>Fu</i> | Load3 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|----------------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | 18 | | Load3 | Yes 64 |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | Yes 80 [80]*R2 |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | 16 | Store2 | Yes 72 [72]*R2 |
| 2 | SD | F4 | 0 | R1 | 8 | | | Store3 | Yes 64 Mult1 |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------------|
| Add1 | No | | | | | | | LD F0 0 R1 |
| Add2 | No | | | | | | | MULTD F4 F0 F2 |
| Add3 | No | | | | | | | SD F4 0 R1 |
| Mult1 | Yes | Multd | | | R(F2) | Load3 | | SUBI R1 R1 #8 ← |
| Mult2 | No | | | | | | | BNEZ R1 Loop |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 18 | 64 | <i>Fu</i> | Load3 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|-----------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | No |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No |
| 1 | SD | F4 | 0 | R1 | 3 | 18 | 19 | Load3 | Yes |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | No |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | 16 | Store2 | Yes |
| 2 | SD | F4 | 0 | R1 | 8 | 19 | | Store3 | Yes |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|----------------|
| Add1 | No | | | | | | | LD F0 0 R1 |
| Add2 | No | | | | | | | MULTD F4 F0 F2 |
| Add3 | No | | | | | | | SD F4 0 R1 |
| Mult1 | Yes | Multd | | | R(F2) | Load3 | | SUBI R1 R1 #8 |
| Mult2 | No | | | | | | | BNEZ R1 Loop ← |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 19 | 56 | <i>Fu</i> | Load3 | | Mult1 | | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Instruction status:

Exec Write

| <i>ITER</i> | <i>Instruction</i> | <i>j</i> | <i>k</i> | <i>Issue</i> | <i>Comp</i> | <i>Result</i> | <i>Busy</i> | <i>Addr</i> | <i>Fu</i> | | |
|-------------|--------------------|----------|----------|--------------|-------------|---------------|-------------|-------------|-----------|----|-------|
| 1 | LD | F0 | 0 | R1 | 1 | 9 | 10 | Load1 | Yes | 56 | |
| 1 | MULTD | F4 | F0 | F2 | 2 | 14 | 15 | Load2 | No | | |
| 1 | SD | F4 | 0 | R1 | 3 | 18 | 19 | Load3 | Yes | 64 | |
| 2 | LD | F0 | 0 | R1 | 6 | 10 | 11 | Store1 | No | | |
| 2 | MULTD | F4 | F0 | F2 | 7 | 15 | 16 | Store2 | No | | |
| 2 | SD | F4 | 0 | R1 | 8 | 19 | 20 | Store3 | Yes | 64 | Mult1 |

Reservation Stations:

S1 S2 RS

| <i>Time</i> | <i>Name</i> | <i>Busy</i> | <i>Op</i> | <i>Vj</i> | <i>Vk</i> | <i>Qj</i> | <i>Qk</i> | <i>Code:</i> | | | |
|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|--------------|----|------|------|
| | Add1 | No | | | | | | LD | F0 | 0 | R1 ← |
| | Add2 | No | | | | | | MULTD | F4 | F0 | F2 |
| | Add3 | No | | | | | | SD | F4 | 0 | R1 |
| | Mult1 | Yes | Multd | | R(F2) | Load3 | | SUBI | R1 | R1 | #8 |
| | Mult2 | No | | | | | | BNEZ | R1 | Loop | |

Register result status

| <i>Clock</i> | <i>R1</i> | <i>F0</i> | <i>F2</i> | <i>F4</i> | <i>F6</i> | <i>F8</i> | <i>F10</i> | <i>F12</i> | <i>...</i> | <i>F30</i> |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|
| 20 | 56 | <i>Fu</i> | Load1 | | | Mult1 | | | | |

Load=8,1

Add=3

Mult=4

SUBI/BNEZ=1

Store=3

Review: Tomasulo Summary

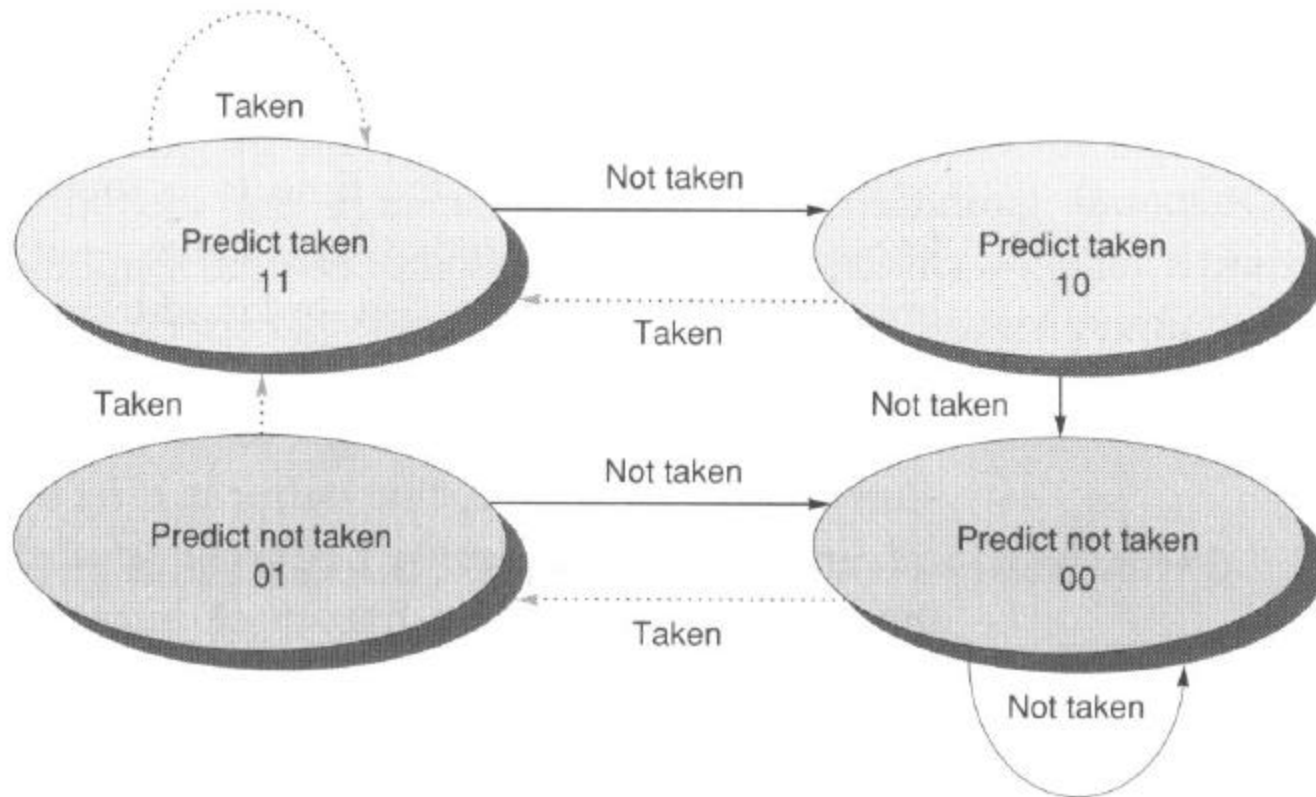
- Registers not the bottleneck
- Avoids the WAR, WAW hazards of Scoreboard
- Not limited to basic blocks (provided branch prediction)
- Allows loop unrolling in HW
- Lasting Contributions
 - Dynamic scheduling
 - Register renaming
 - Load/store disambiguation

Dynamic Branch Prediction

- Performance = $f(\text{accuracy, cost of misprediction})$
- Branch History Table (BHT) is simplest
 - Lower bits of PC address index table of 1-bit values
 - Says whether or not branch taken last time
- Problem: in a loop, 1-bit BHT will cause two mispredictions:
 - Previous loop finishes, sets to not taken
 - Next loop is taken (1 mispredict)
 - Last iteration of this loop is not taken (1 mispredict)

Dynamic Branch Prediction

- Solution: 2-bit scheme where change prediction only if get misprediction *twice*:



BHT Accuracy

- Mispredict because either:
 - Wrong guess for that branch
 - Got branch history of wrong branch when index the table
 - “Based on recent behavior of a single branch” to predict
- 4096 entry table programs vary from 1% misprediction (nasa7, tomcatv) to 18% (eqntott), with spice at 9% and gcc at 12%
- 4096 about as good as infinite table, but 4096 is a lot of HW
- Recent behavior of this branch not enough (series of if stmt's)

Correlating Branch Predictors

- Idea: taken/not taken of recently executed branches is related to the behaviors of other branches (as well as its own history)
- Example

```
Bnez  R1, L1      ; b1
Dadd  R1, R0, #1
L1: Dsub R3, R1, #1
      Bnez  R3, L2      ;b2
      ....
L2:
```

Assume:

R1 = 2,0,2,0,....

1-bit predictor initialized to untaken
what happens?

Example

```
Bnez R1, L1 ; b1
Dadd R1, R0, #1
L1: Dsub R3, R1, #1
Bnez R3, L2 ;b2
....
L2:
```

| Init R1 | P _{b1} | A _{b1} | N _{b1} | P _{b2} | A _{b2} | N _{b2} |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2 | NT | T | T | NT | T | T |
| 0 | T | NT | NT | T | NT | NT |
| 2 | NT | T | T | NT | T | T |

Correlating Branch Predictors

- (m,n) predictor
 - Using the behaviors of the previous m branches to predict current branch
 - Total n bit to predict a single branch
- Example:
 - (1,1) predictor
 - Using the behaviors of the previous branch (two possibilities)
 - Using 1-bit to predict each branch

Example

```

Bnez  R1, L1      ; b1
Dadd  R1, R0, #1
L1:   Dsub R3, R1, #1
      Bnez  R3, L2      ;b2
      ....
L2:

```

| d | P _{b1} | A _{b1} | N _{b1} | P _{b2} | A _{b2} | N _{b2} |
|---|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2 | <u>NT</u> /NT | T | T/NT | NT/ <u>NT</u> | T | NT/T |
| 0 | T/ <u>NT</u> | NT | T/NT | <u>NT</u> /T | NT | NT/T |
| 2 | <u>T</u> /NT | T | T/NT | NT/ <u>T</u> | T | NT/T |

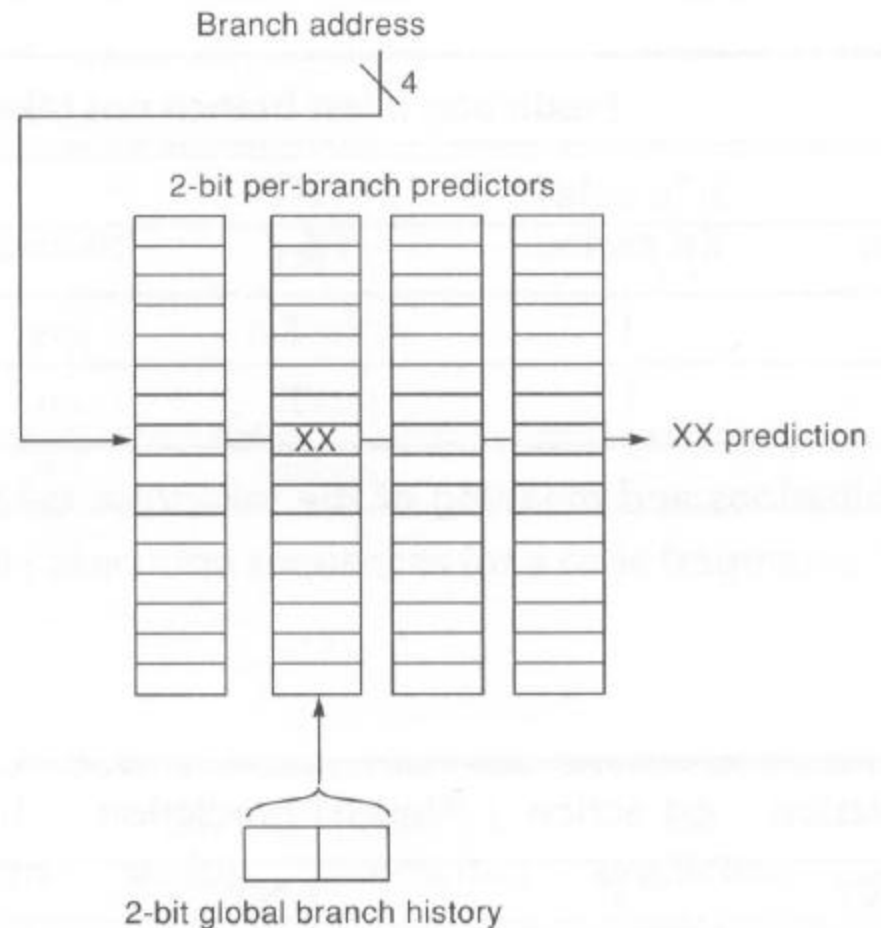
Prediction if the last branch of the program is...

↑ ↑
 NT T

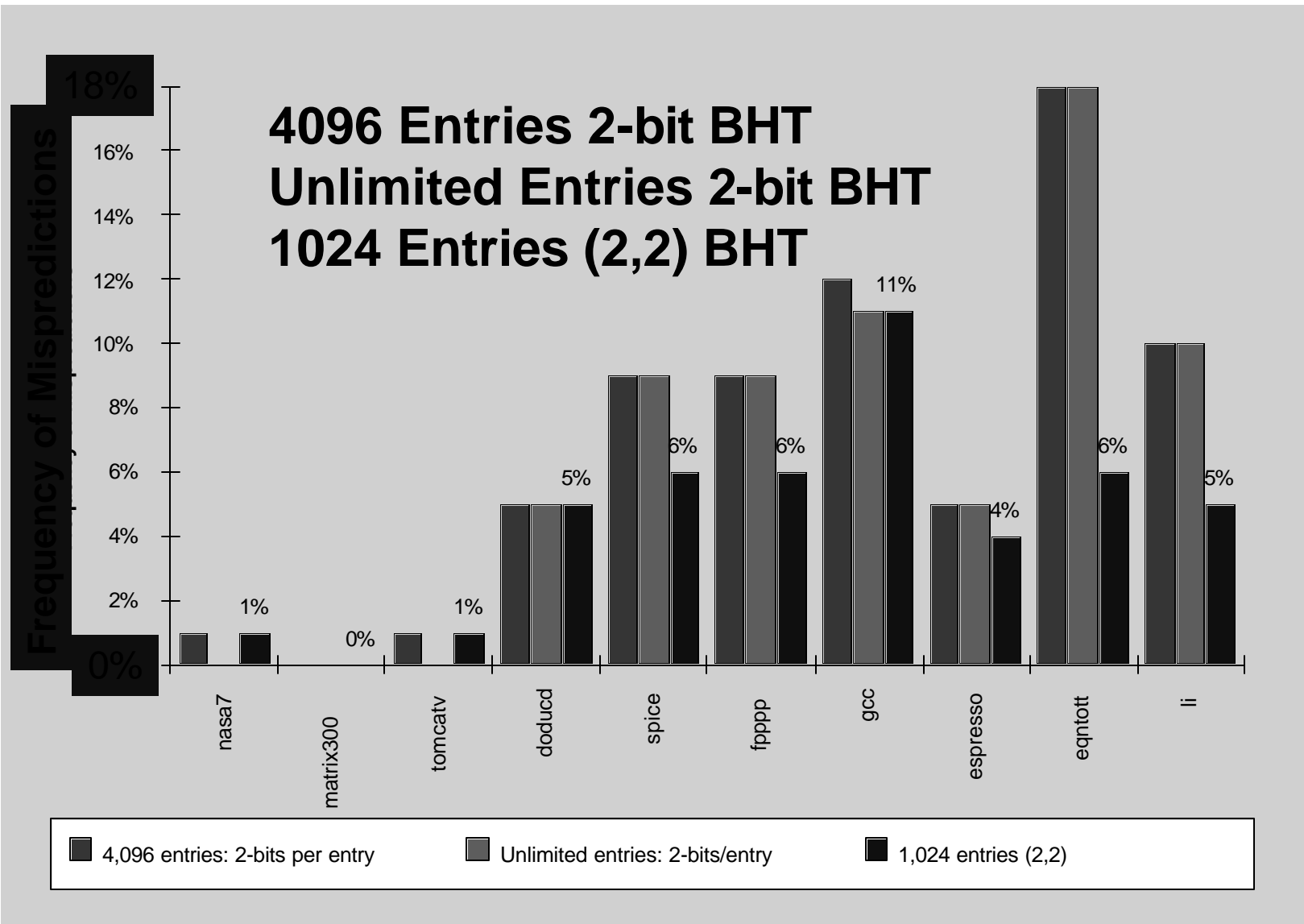
Correlating Branches

Idea: taken/not taken of recently executed branches is related to behavior of next branch (as well as the history of that branch behavior)

- Then behavior of recent branches selects between, say, four predictions of next branch, updating just that prediction
- Ex: If B1 not taken, then B2 not taken



Accuracy of Different Schemes

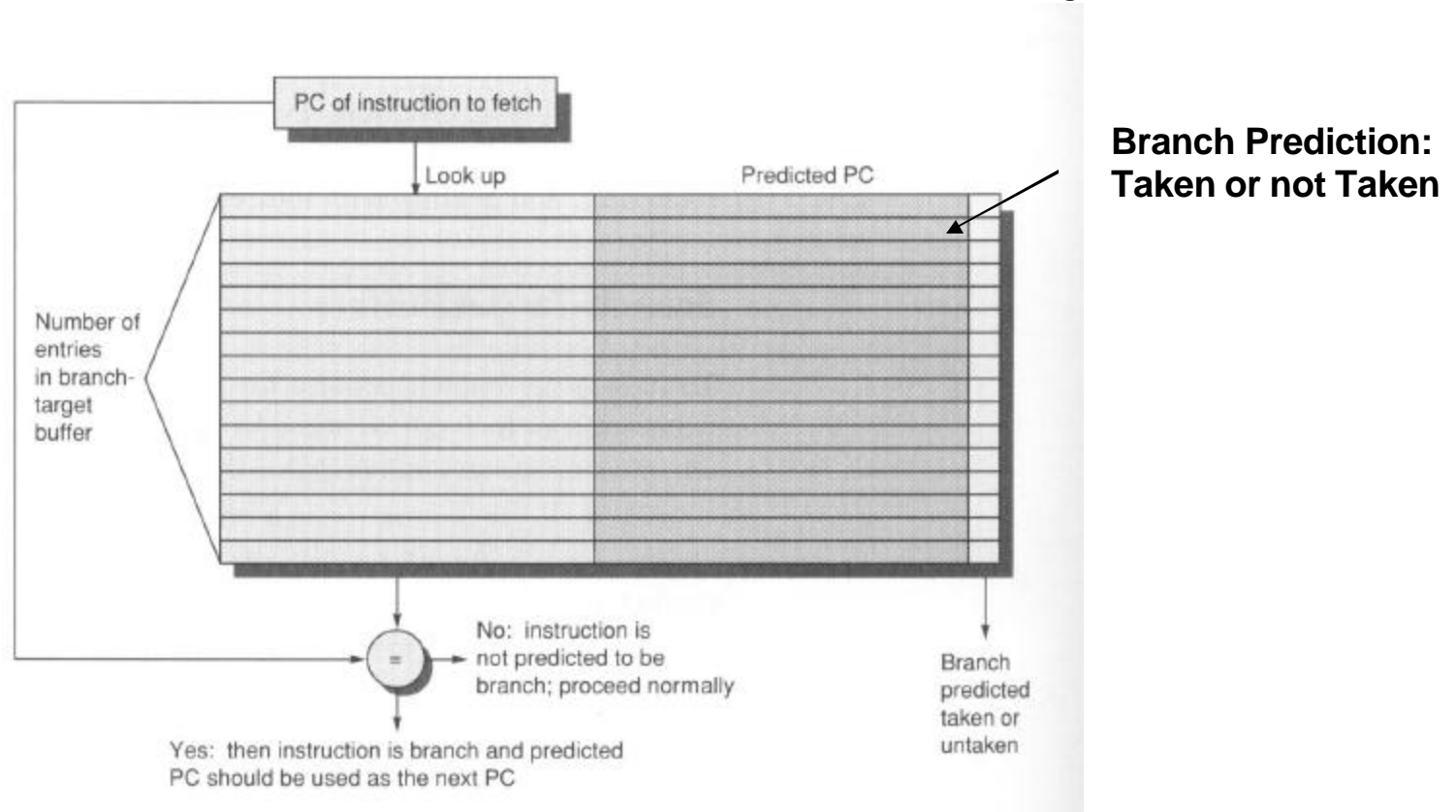


Branch Prediction Buffer Size

- For a (m,n) predictor
size = $2^m \times n \times \#_of_entries$
- For 8K buffer, how many entries for (2,2) predictors?
 $2^2 \times 2 \times N = 8K$ therefore $N = 1K$

Need Address @ Same Time as Prediction

- Branch Target Buffer (BTB): Address of branch index to get prediction AND branch address (if taken)
 - Note: must check for branch match now, since can't use wrong branch address



- Return instruction addresses predicted with stack

Branch-Target Buffers

