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CS61C : Machine Structures

Lecture 30 – Pipelined Execution, part II

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Games to learn?! ⇒

Recent studies show that there may be a place for computer games in traditional K-12 classrooms. There is data that shows dropout rates are lower, SATs, enjoyment, interest up!

www.technologyreview.com/articles/05/04/wo/wo_040605krotoski.asp

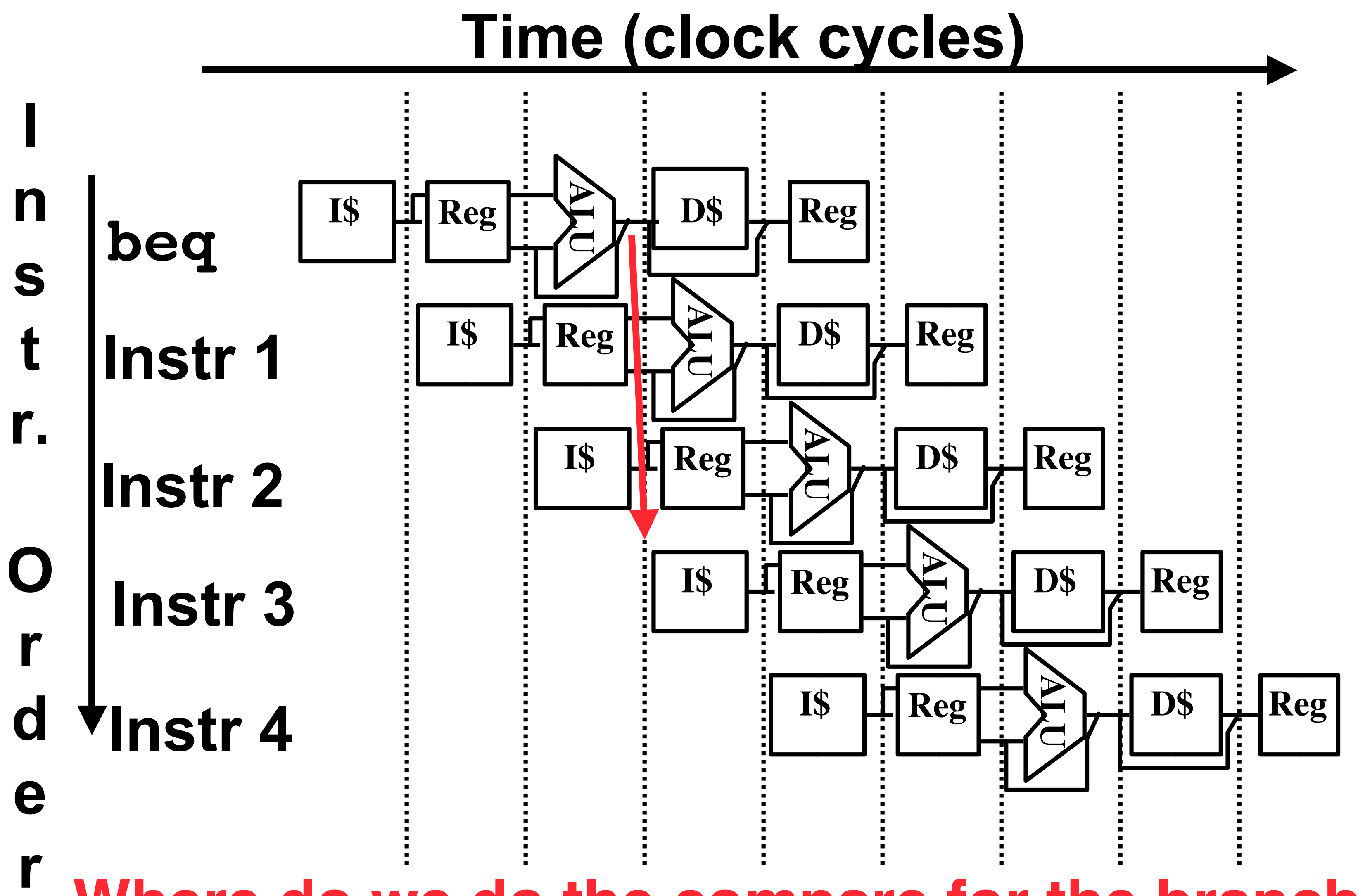
Review: Pipeline (1/2)

- Optimal Pipeline
  - Each stage is executing part of an instruction each clock cycle.
  - One inst. finishes during <u>each</u> clock cycle.
  - On average, execute far more quickly.
- What makes this work?
  - Similarities between instructions allow us to use same stages for all instructions (generally).
  - Each stage takes about the same amount of time as all others: little wasted time.

Review: Pipeline (2/2)

- Pipelining is a BIG IDEA
  - widely used concept
- What makes it less than perfect?
  - Structural hazards: suppose we had only one cache?
    ⇒ Need more HW resources
  - Control hazards: need to worry about branch instructions?
    ⇒ Delayed branch
  - Data hazards: an instruction depends on a previous instruction?

Control Hazard: Branching (1/7)



Where do we do the compare for the branch?

Control Hazard: Branching (2/7)

- We put branch decision-making hardware in ALU stage
  - therefore two more instructions after the branch will *always* be fetched, whether or not the branch is taken
- Desired functionality of a branch
  - if we do not take the branch, don’t waste any time and continue executing normally
  - if we take the branch, don’t execute any instructions after the branch, just go to the desired label

Control Hazard: Branching (3/7)

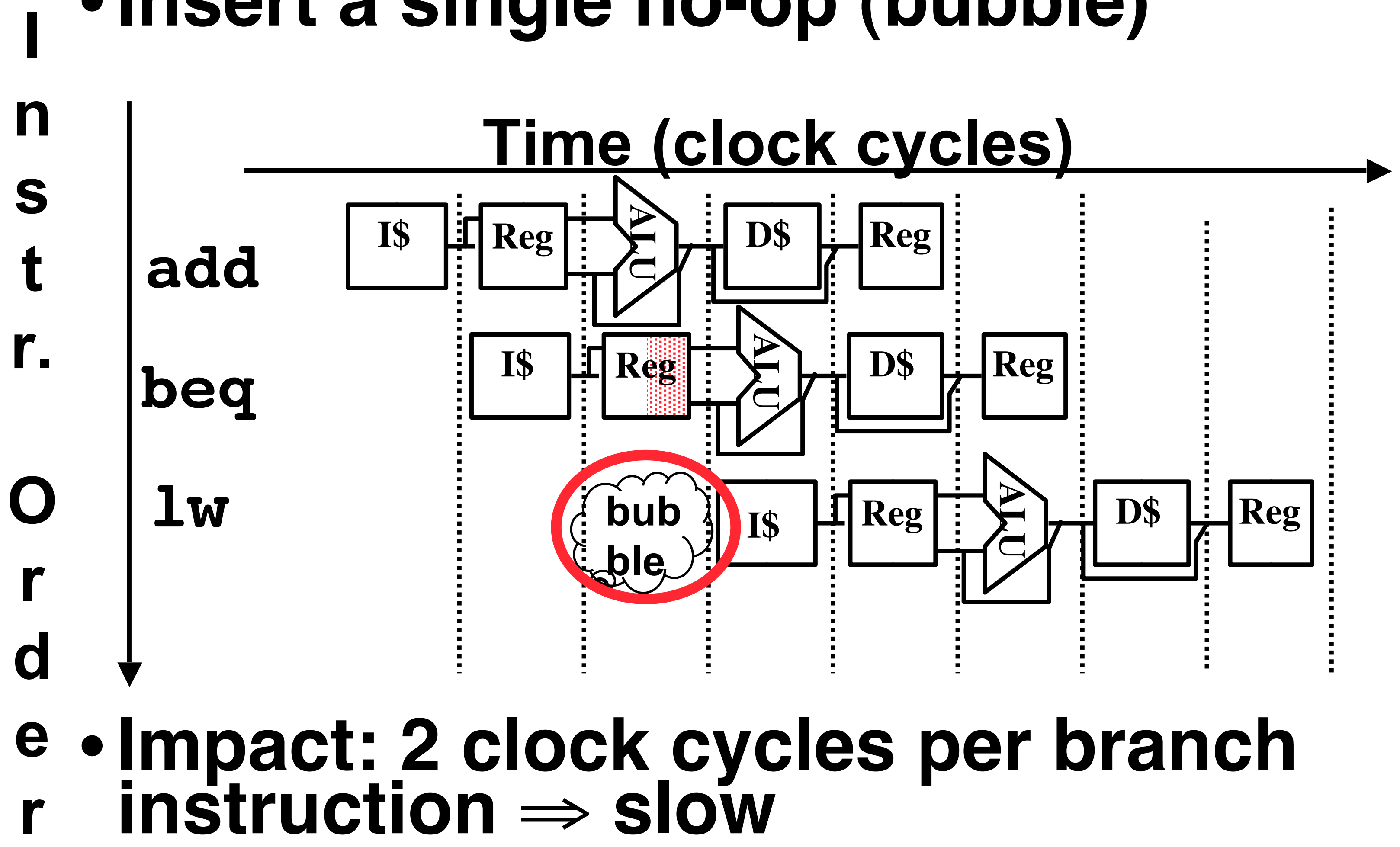
- Initial Solution: Stall until decision is made
    - insert “no-op” instructions: those that accomplish nothing, just take time
    - Drawback: branches take 3 clock cycles each (assuming comparator is put in ALU stage)

Control Hazard: Branching (4/7)

- Optimization #1:
  - move asynchronous comparator up to Stage 2
  - as soon as instruction is decoded (Opcode identifies is as a branch), immediately make a decision and set the value of the PC (if necessary)
  - Benefit: since branch is complete in Stage 2, only one unnecessary instruction is fetched, so only one no-op is needed
  - Side Note: This means that branches are idle in Stages 3, 4 and 5.

Control Hazard: Branching (5/7)

- Insert a single no-op (bubble)



- Impact: 2 clock cycles per branch instruction ⇒ slow

Control Hazard: Branching (6/7)

- Optimization #2: Redefine branches
  - Old definition: if we take the branch, none of the instructions after the branch get executed by accident
  - New definition: whether or not we take the branch, the single instruction immediately following the branch gets executed (called the branch-delay slot)
- The term "Delayed Branch" means we always execute inst after branch

Control Hazard: Branching (7/7)

- Notes on Branch-Delay Slot
  - Worst-Case Scenario: can always put a no-op in the branch-delay slot
  - Better Case: can find an instruction preceding the branch which can be placed in the branch-delay slot without affecting flow of the program
    - re-ordering instructions is a common method of speeding up programs
    - compiler must be very smart in order to find instructions to do this
    - usually can find such an instruction at least 50% of the time
    - Jumps also have a delay slot…

Example: Nondelayed vs. Delayed Branch

Nondelayed Branch

```
or    $8, $9 ,$10

add $1 ,$2,$3

sub $4, $5,$6

beq $1, $4, Exit

xor $10, $1,$11

Exit:
```

Delayed Branch

```
add $1 ,$2,$3

sub $4, $5,$6

beq $1, $4, Exit

or    $8, $9 ,$10

xor $10, $1,$11

Exit:
```

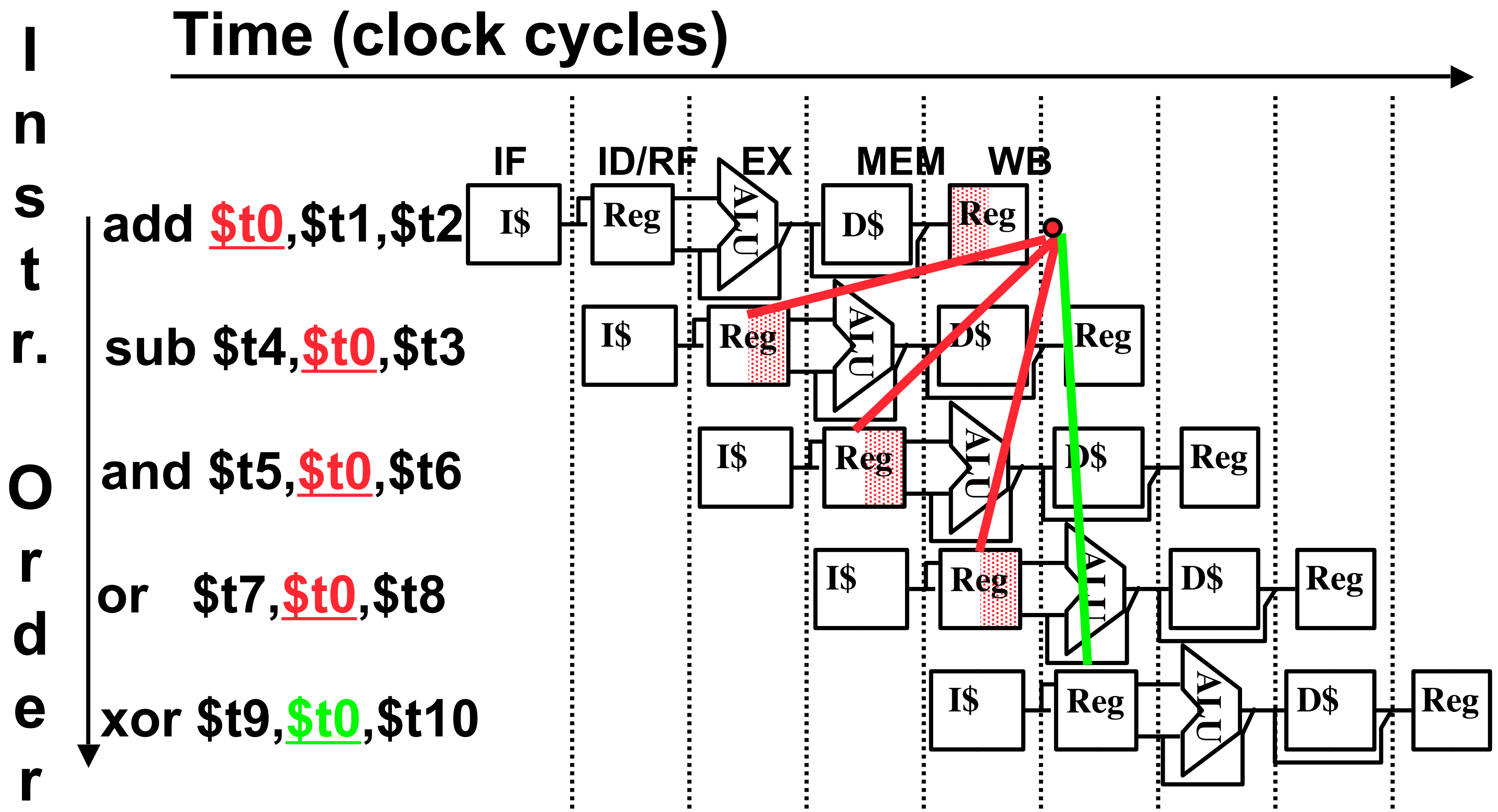
Data Hazards (1/2)

- **Consider the following sequence of instructions**

```
add $t0, $t1, $t2

sub $t4, $t0 ,$t3

and $t5, $t0 ,$t6

or  $t7, $t0 ,$t8

xor $t9, $t0 ,$t10
```

Data Hazards (2/2)

Dependencies backwards in time are hazards



Data Hazard Solution: Forwarding

- **Forward** result from one stage to another

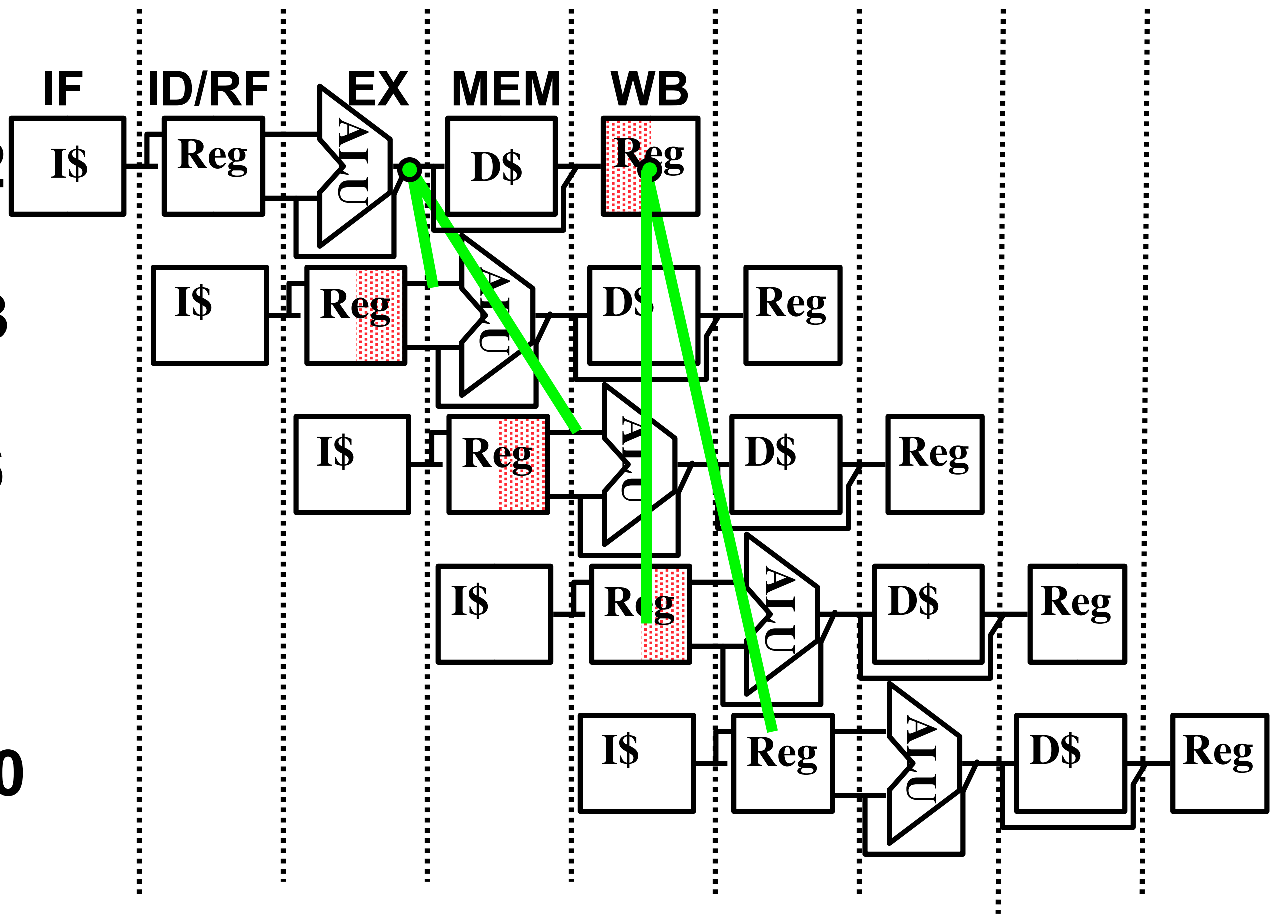
add $t0,$t1,$t2

sub $t4,$t0,$t3

and $t5,$t0,$t6

or $t7,$t0,$t8

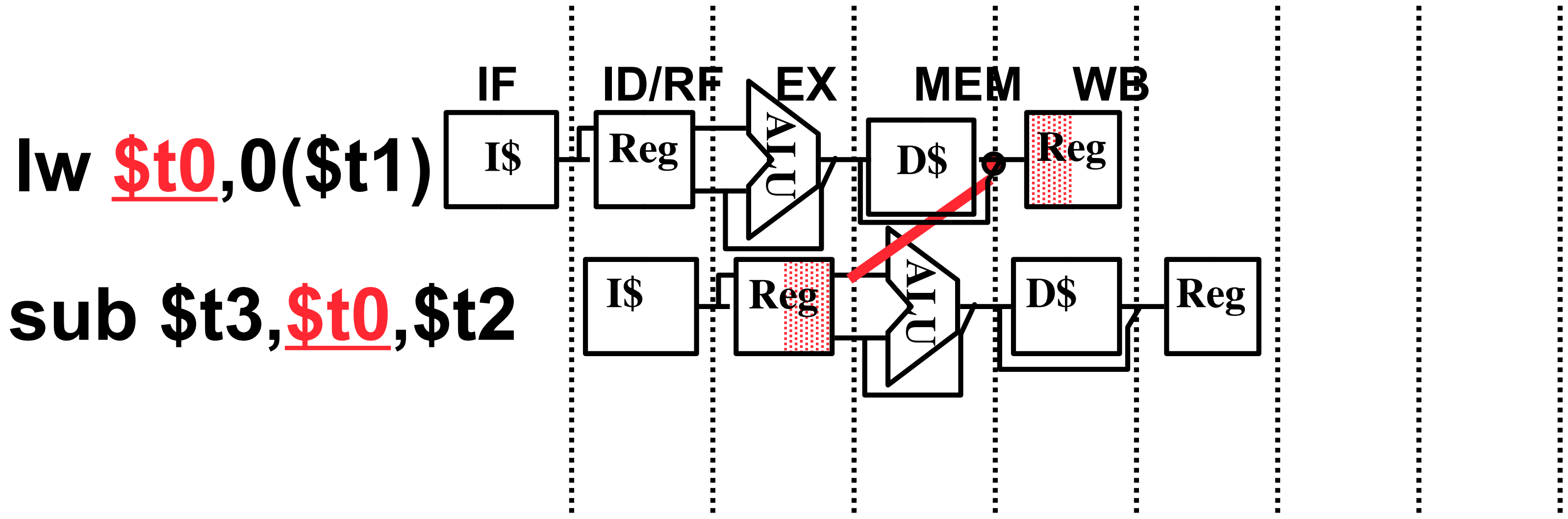
xor $t9,$t0,$t10



"`or`" hazard solved by register hardware

Data Hazard: Loads (1/4)

- Dependencies backwards in time are hazards



- Can’t solve with forwarding
- Must stall instruction dependent on load, then forward (more hardware)

Data Hazard: Loads (2/4)

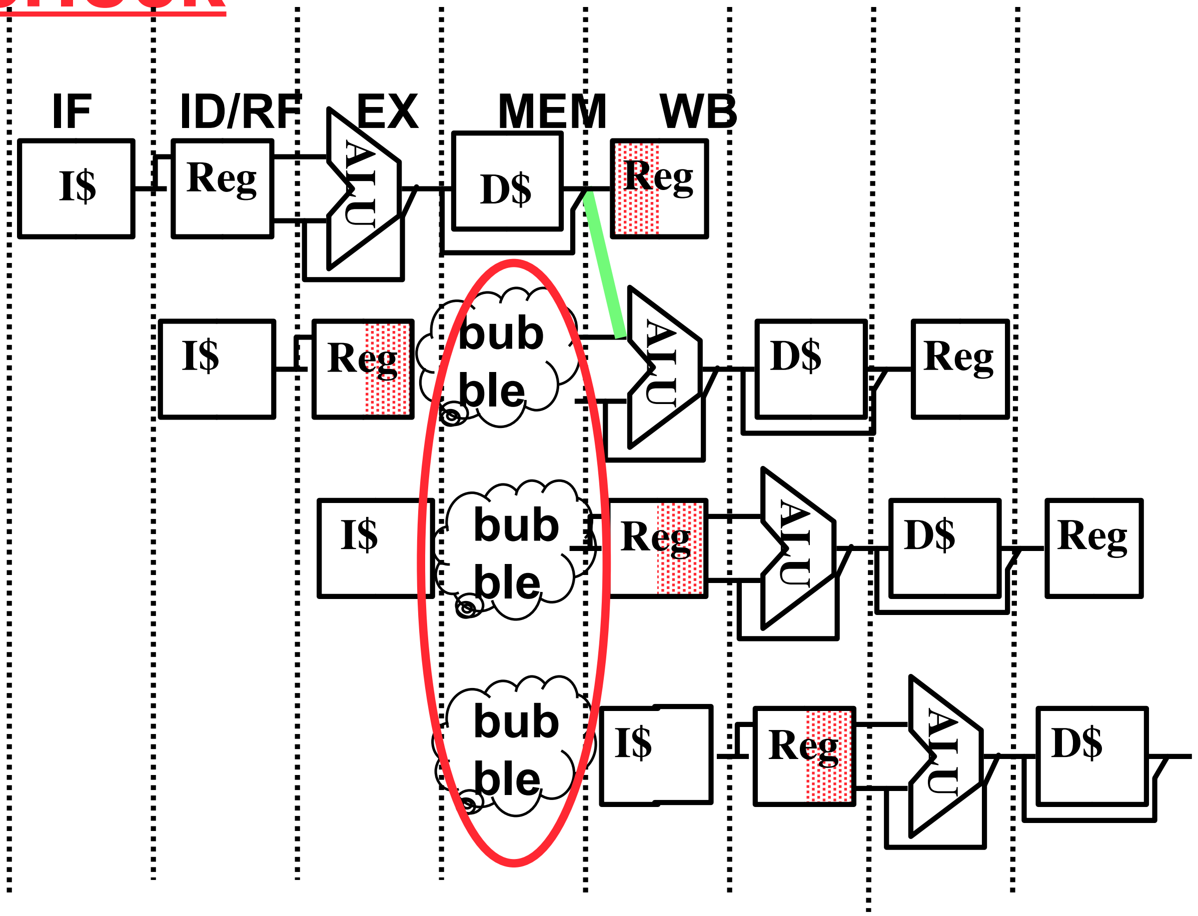
- Hardware must stall pipeline
- Called "interlock"

lw $t0, 0($t1)

sub $t3,$t0,$t2

and $t5,$t0,$t4

or $t7,$t0,$t6



Data Hazard: Loads (3/4)

- Instruction slot after a load is called "load delay slot"
- If that instruction uses the result of the load, then the hardware interlock will stall it for one cycle.
- If the compiler puts an unrelated instruction in that slot, then no stall
- Letting the hardware stall the instruction in the delay slot is equivalent to putting a nop in the slot (except the latter uses more code space)

Data Hazard: Loads (4/4)

- Stall is equivalent to nop

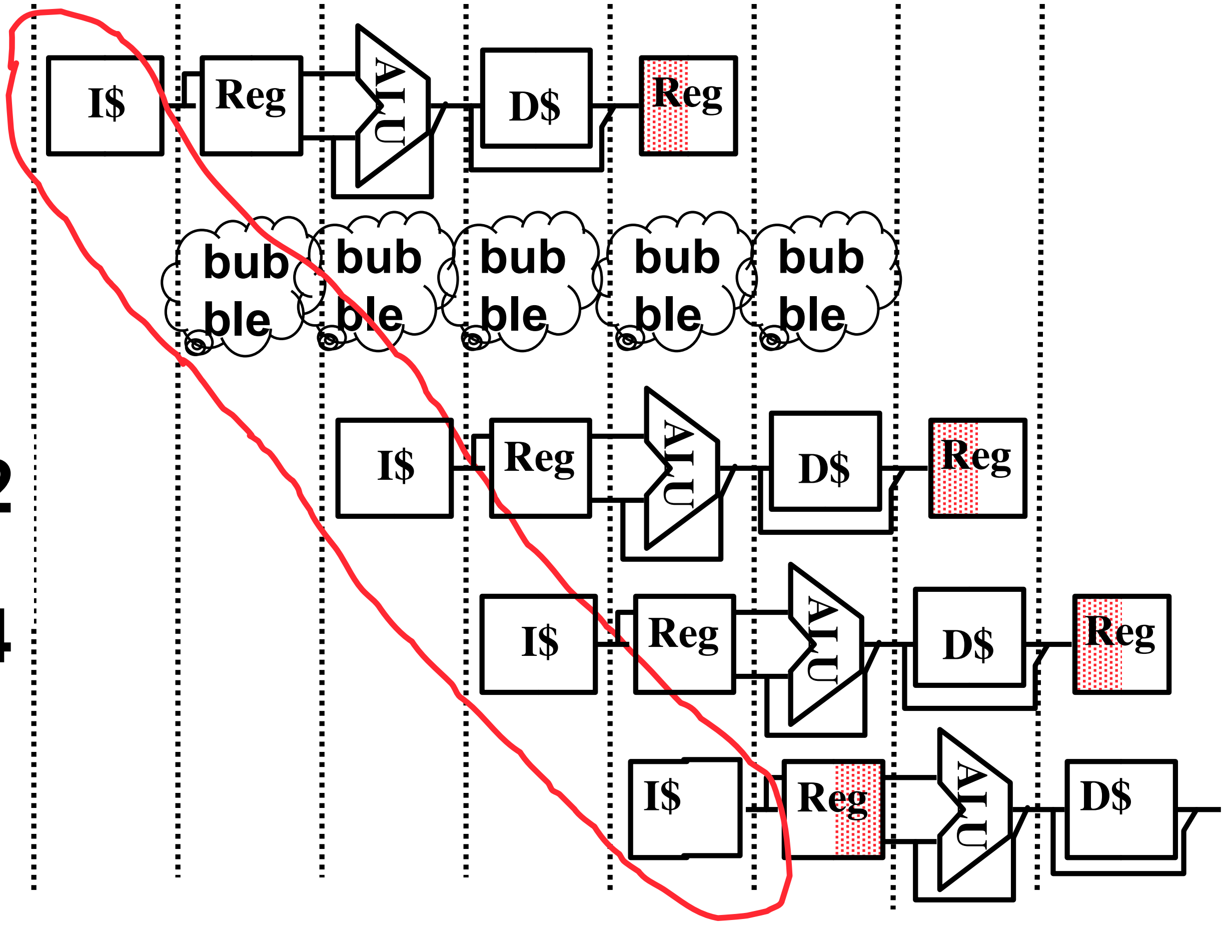
lw $t0, 0($t1)

nop

sub $t3,$t0,$t2

and $t5,$t0,$t4

or $t7,$t0,$t6



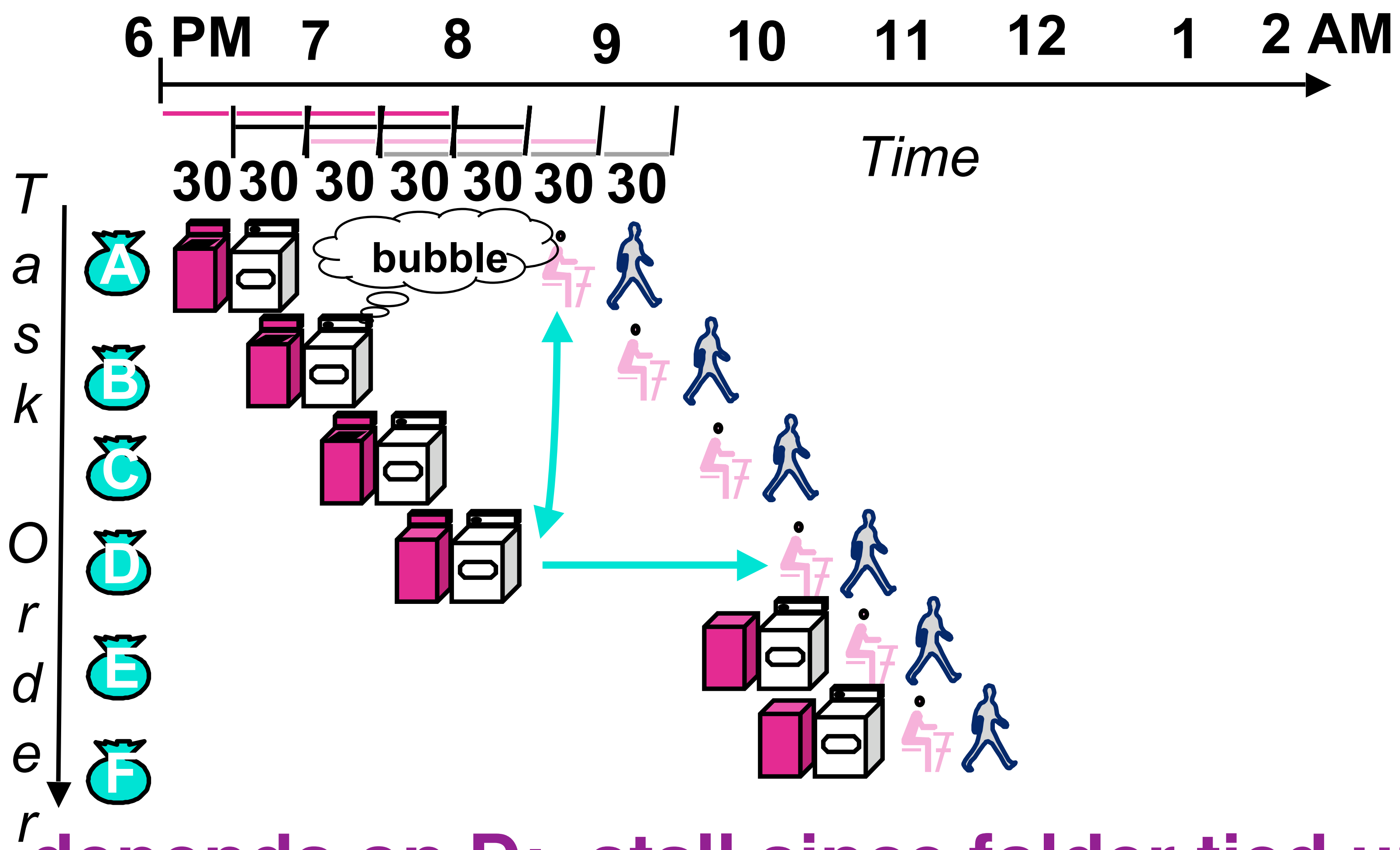
Historical Trivia

- First MIPS design did not interlock and stall on load-use data hazard
- Real reason for name behind MIPS:
  Microprocessor without
  Interlocked
  Pipeline
  Stages
  - Word Play on acronym for
    Millions of Instructions Per Second,
    also called MIPS

Administrivia

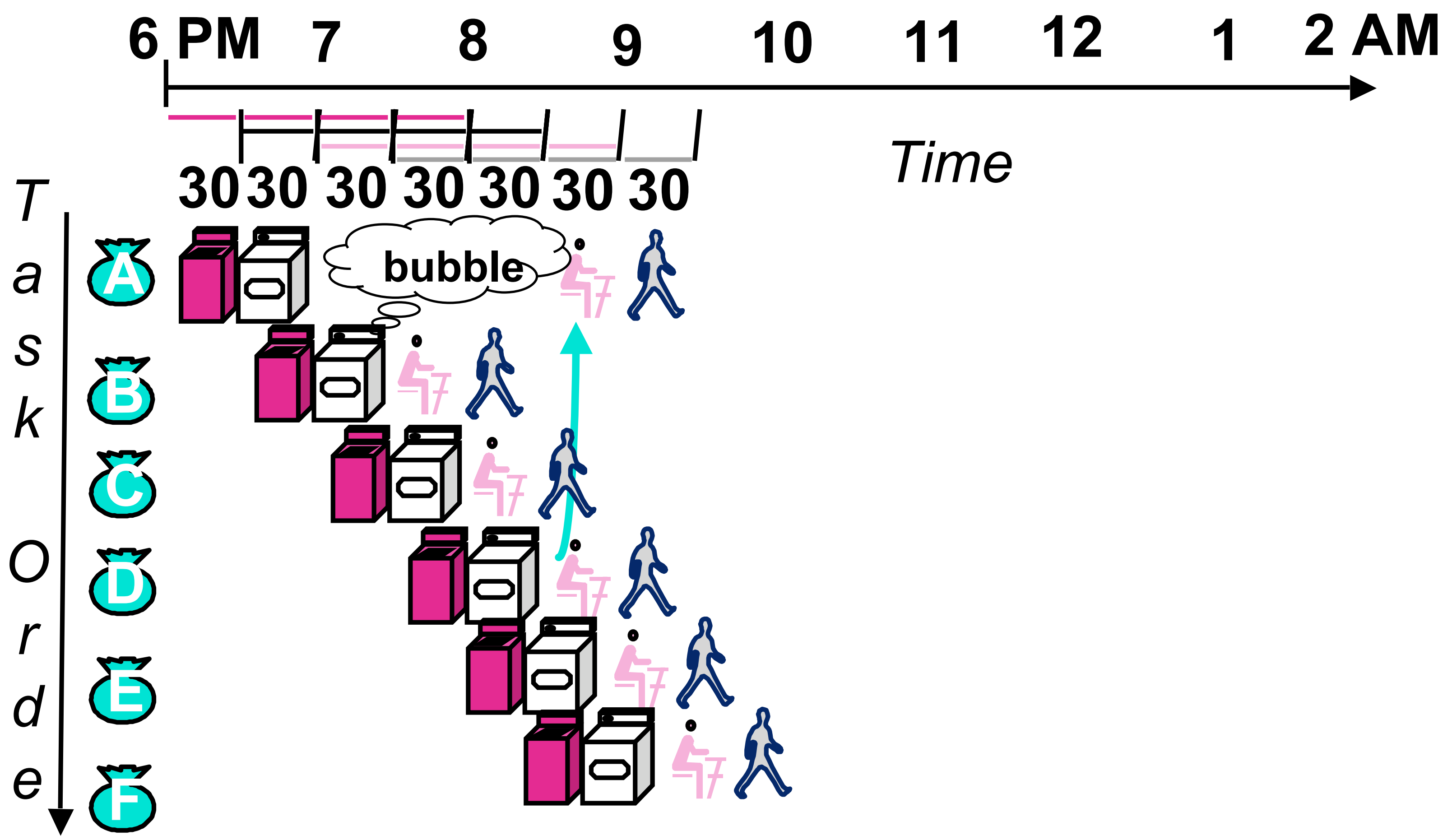
- Any administrivia?
- Advanced Pipelining!
  - "Out-of-order" Execution
  - "Superscalar" Execution

Review Pipeline Hazard: Stall is dependency



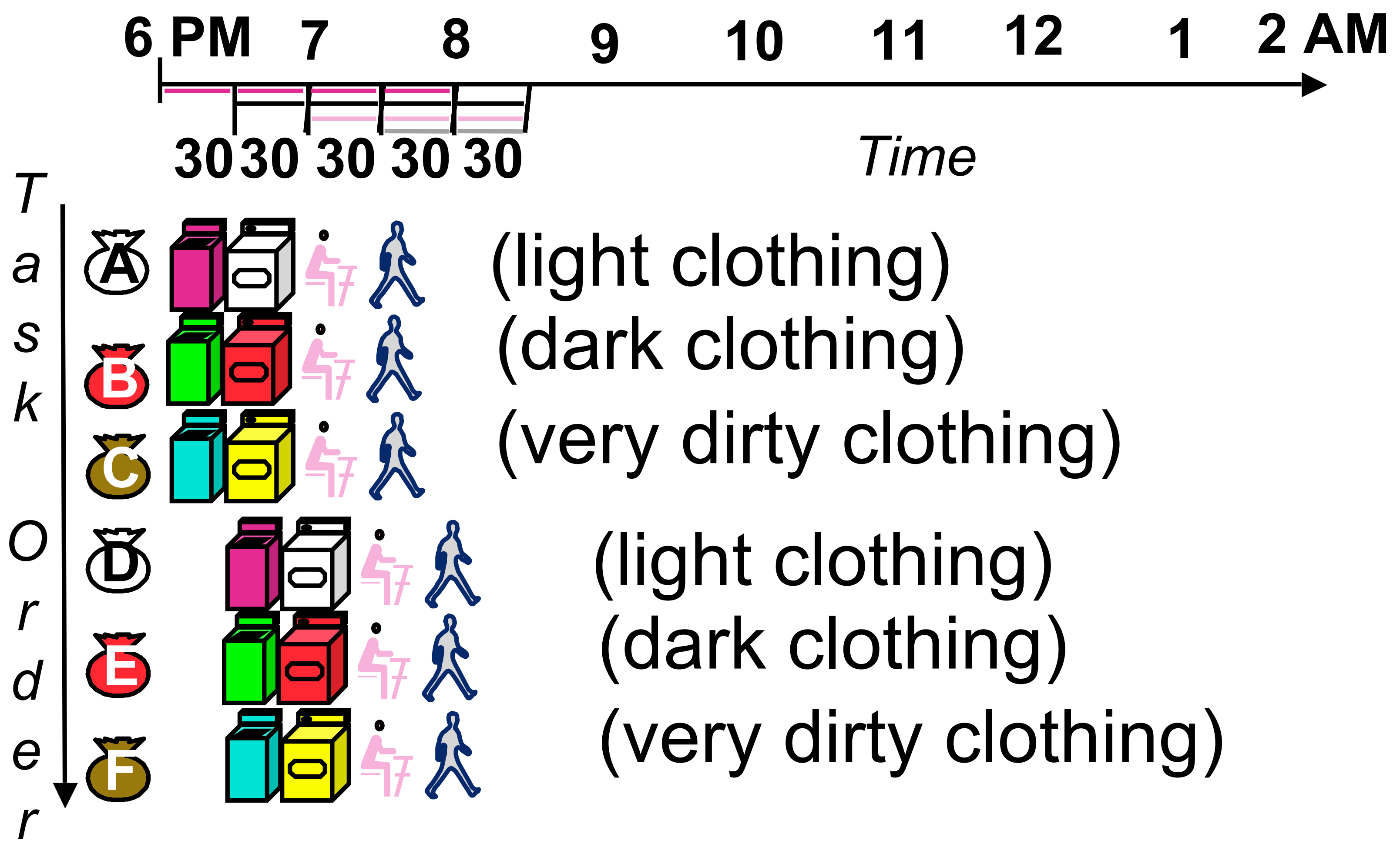
A depends on D; stall since folder tied up

Out-of-Order Laundry: Don't Wait



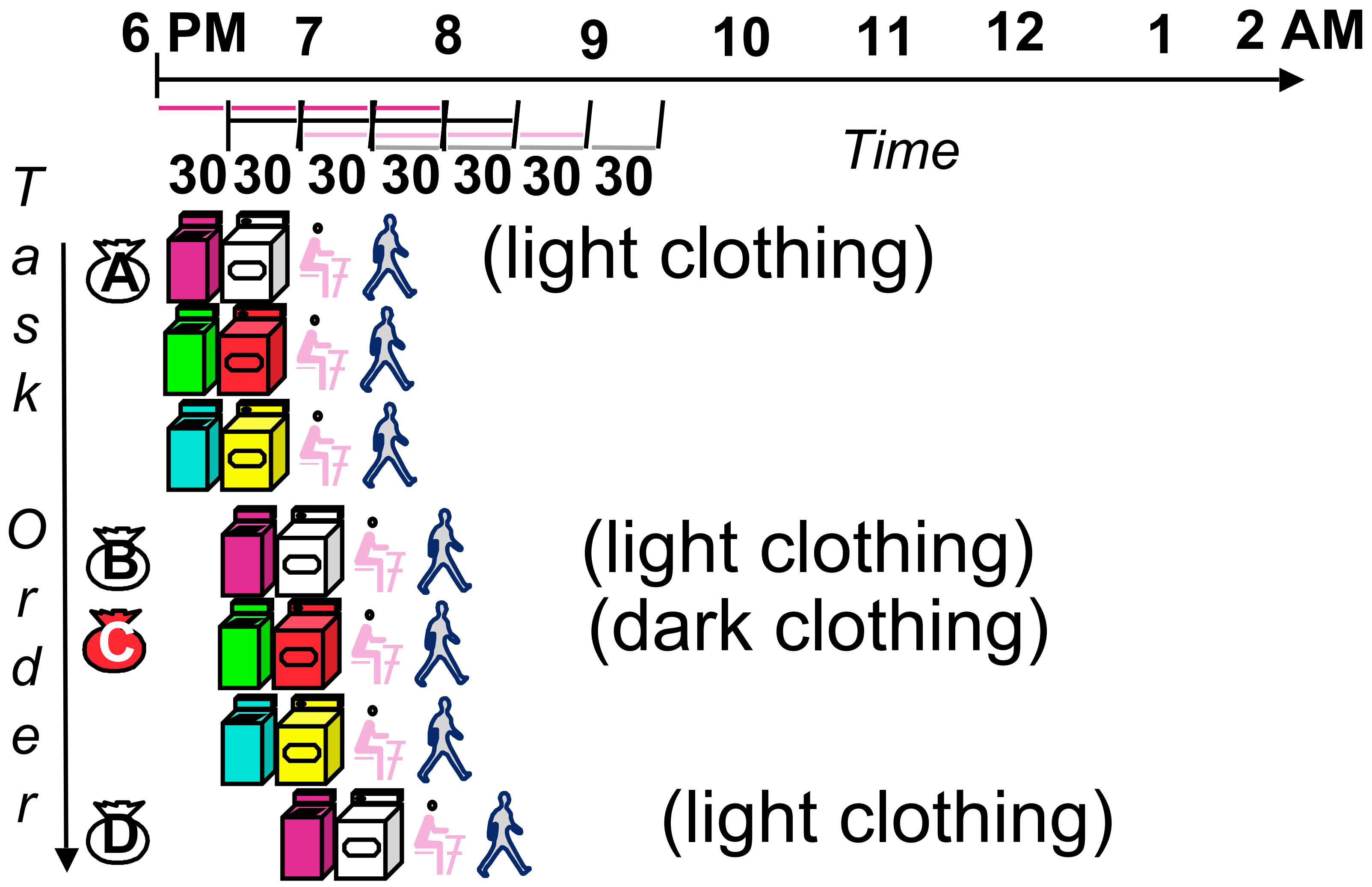
A depends on D; rest continue; need more resources to allow out-of-order

Superscalar Laundry: Parallel per stage



More resources, HW to match mix of parallel tasks?

Superscalar Laundry: Mismatch Mix



Task mix underutilizes extra resources

Peer Instruction

Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards (after 10^3 loops, so pipeline full)

```
Loop:     lw    $t0, 0($s1)
          addu  $t0, $t0, $s2
          sw    $t0, 0($s1)
          addiu $s1, $s1, -4
          bne   $s1, $zero, Loop
          nop
```

- **How many pipeline stages (clock cycles) per loop iteration to execute this code?**

1
2
3
4
5
6
7
8
9
10

Peer Instruction Answer

- Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards. 10^3 iterations, so pipeline full.

2. (data hazard so stall)

```
Loop: 1. lw    $t0, 0($s1)
      3. addu  $t0, $t0, $s2
      4. sw    $t0, 0($s1)
      5. addiu $s1, $s1, -4
      6. bne   $s1, $zero, Loop
      7. nop
```

(delayed branch so exec. nop)

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

1 2 3 4 5 6 [✓ 7] 8 9 10

“And in Conclusion..”

- Pipeline challenge is hazards
  - Forwarding helps w/many data hazards
  - Delayed branch helps with control hazard in 5 stage pipeline
- More aggressive performance:
  - Superscalar
  - Out-of-order execution