CS429: Computer Organization and Architecture

Pipeline I

Warren Hunt, Jr. and Bill Young
Department of Computer Sciences
University of Texas at Austin

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Overview

What's wrong with the sequential (SEQ) Y86?

- It's slow!
- Each piece of hardware is used only a small fraction of the time.
- We would like to find a way to get more performance with only a little more hardware.

General Principles of Pipelining

- Express task as a collection of stages
- Move instructions through stages
- Process several instructions at any given moment

Creating a Pipelined Y86 Processor

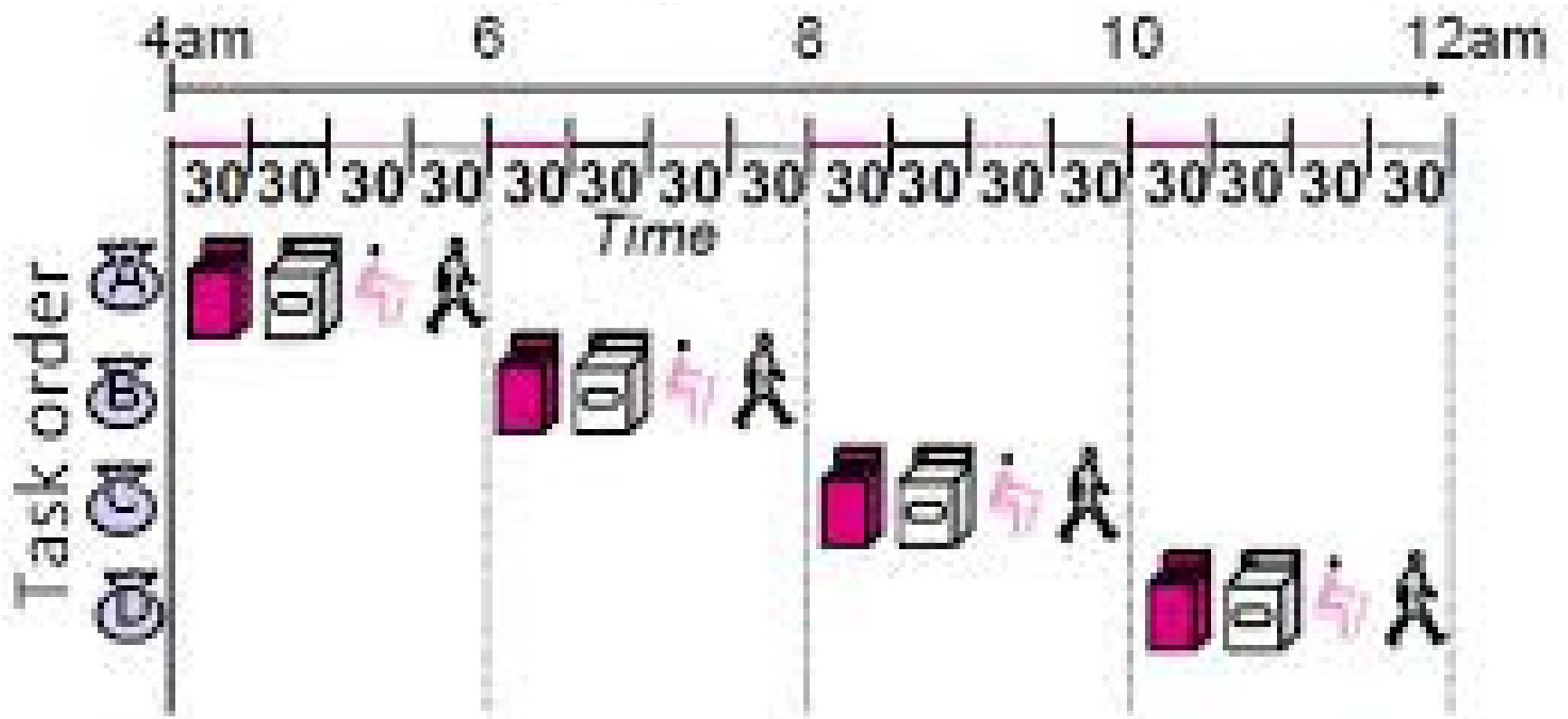
- Rearrange SEQ
- Insert pipeline registers
- Deal with data and control hazards

Pipelining: Laundry Example

Suppose you have four folks, each with a load of clothes to wash, dry, fold and stash away. There are four subtasks: wash, dry, fold, stash. Each takes 30 minutes.

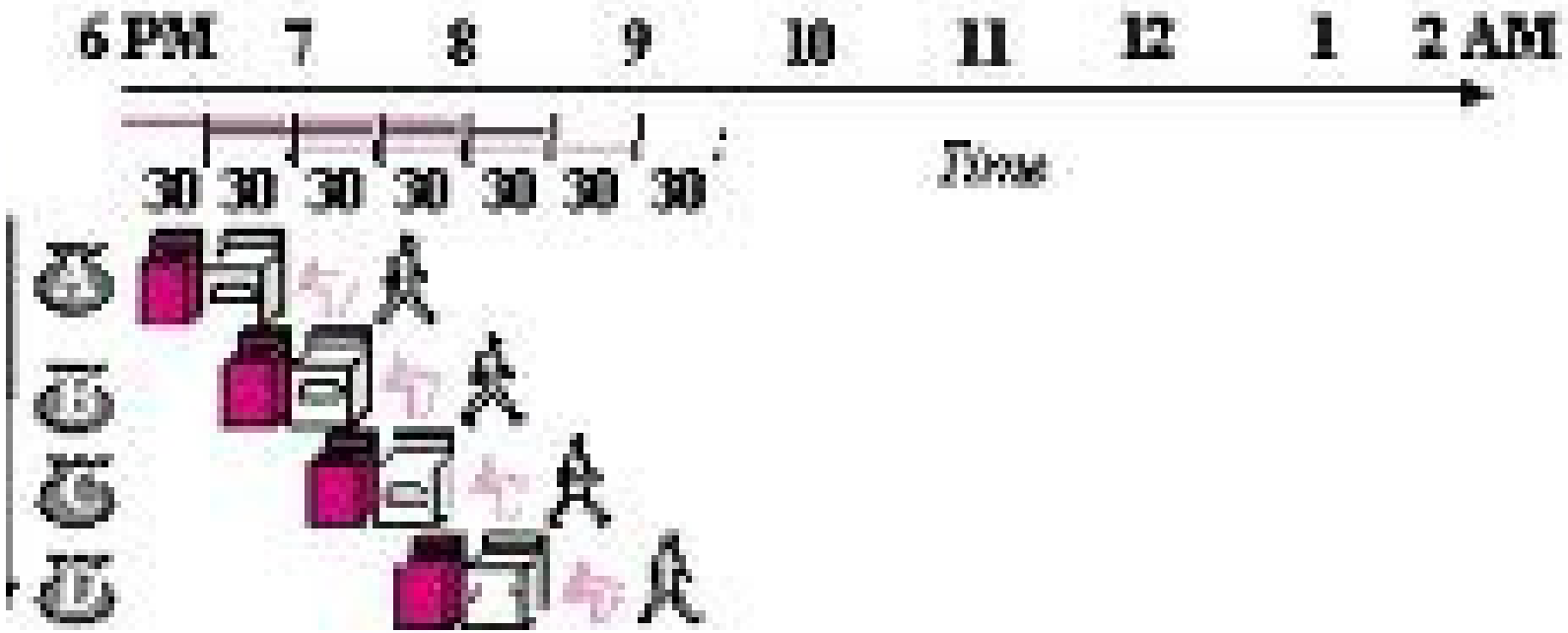
Time to do a load of laundry from start to finish: 2 hours.

Sequential Laundry



- Sequential laundry takes 8 hours for 4 loads.
- If they learned pipelining, how long would laundry take?

Pipelined Laundry

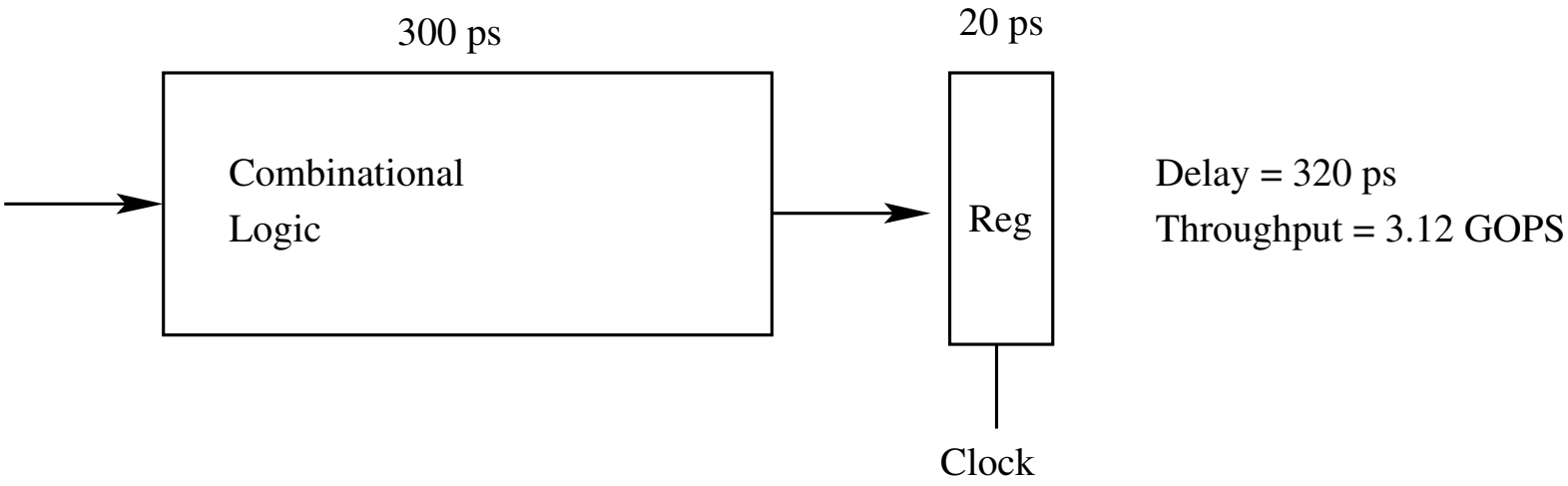


Pipelined laundry takes 3.5 hours for 4 loads!

Pipelining Lessons

- Pipelining doesn't help *latency* of a single task; it helps *throughput* of the entire workload.
- Multiple tasks operate simultaneously using different resources.
- Potential speedup = number of stages.
- Unbalanced lengths of pipe stages reduces speedup.
- Time to "fill" pipeline and time to "drain" it reduces speedup.
- Stall for dependencies.

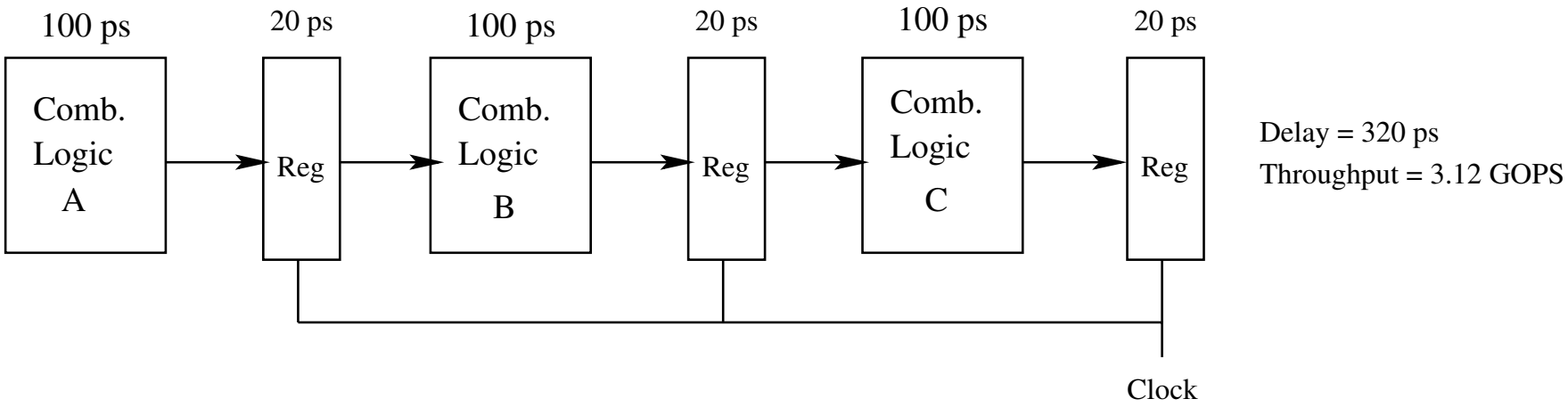
Computational Example



System

- Computation requires a total of 300 picoseconds.
- Needs an additional 20 picoseconds to save the result in the register.
- Must have a clock cycle of at least 320 ps. Why?

3-Way Pipelined Version

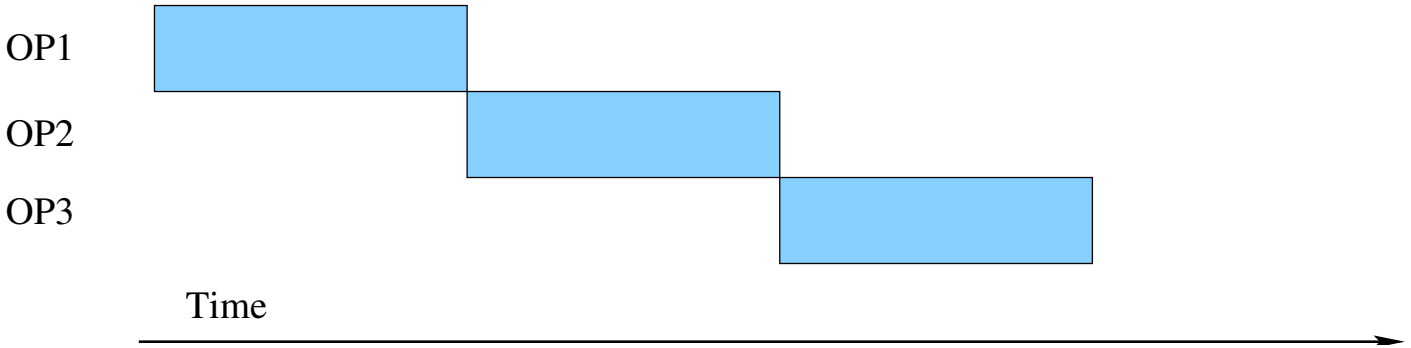


System

- Divide combinational logic into 3 blocks of 100 ps each.
- Can begin a new operation as soon as the previous one passes through stage A.
- Begin new operation every 120 ps. Why?
- Overall latency *increases*! It's now 360 ps from start to finish.

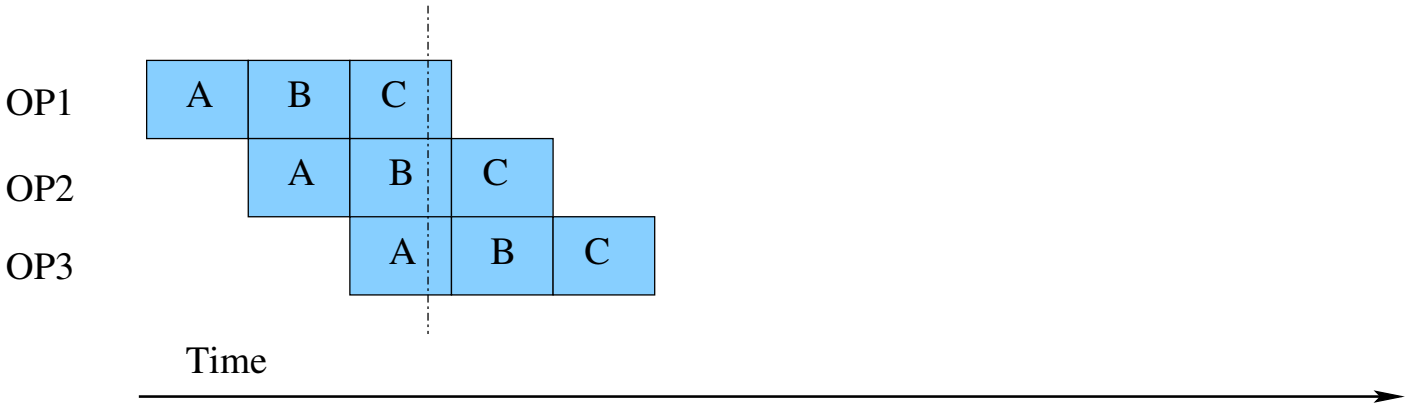
Pipeline Diagrams

Unpipelined



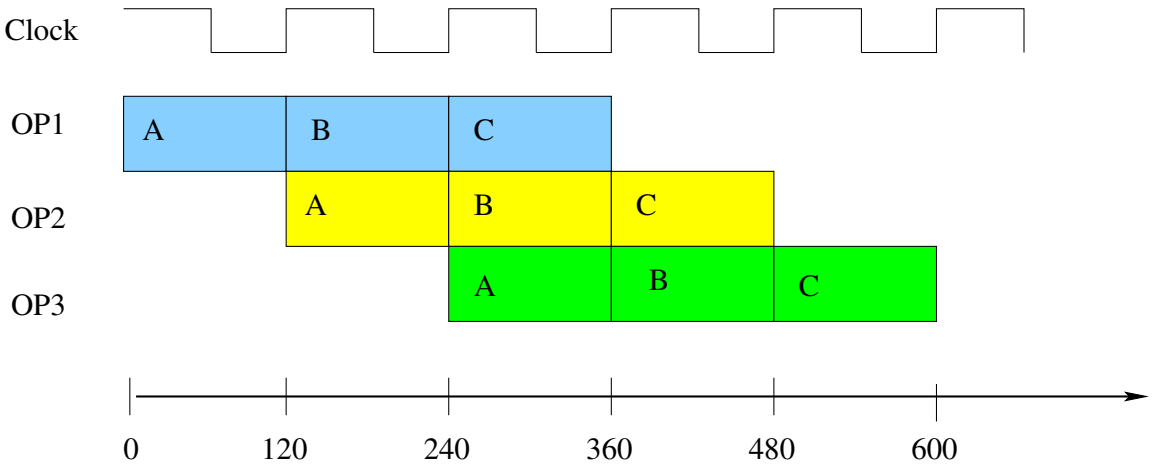
Cannot start new operation until the previous one completes.

3-Way Pipelined

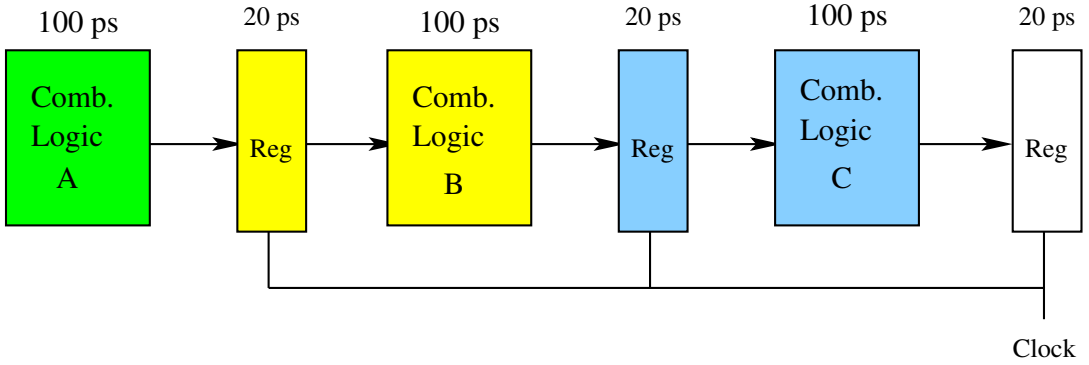


Up to 3 operations in process simultaneously.

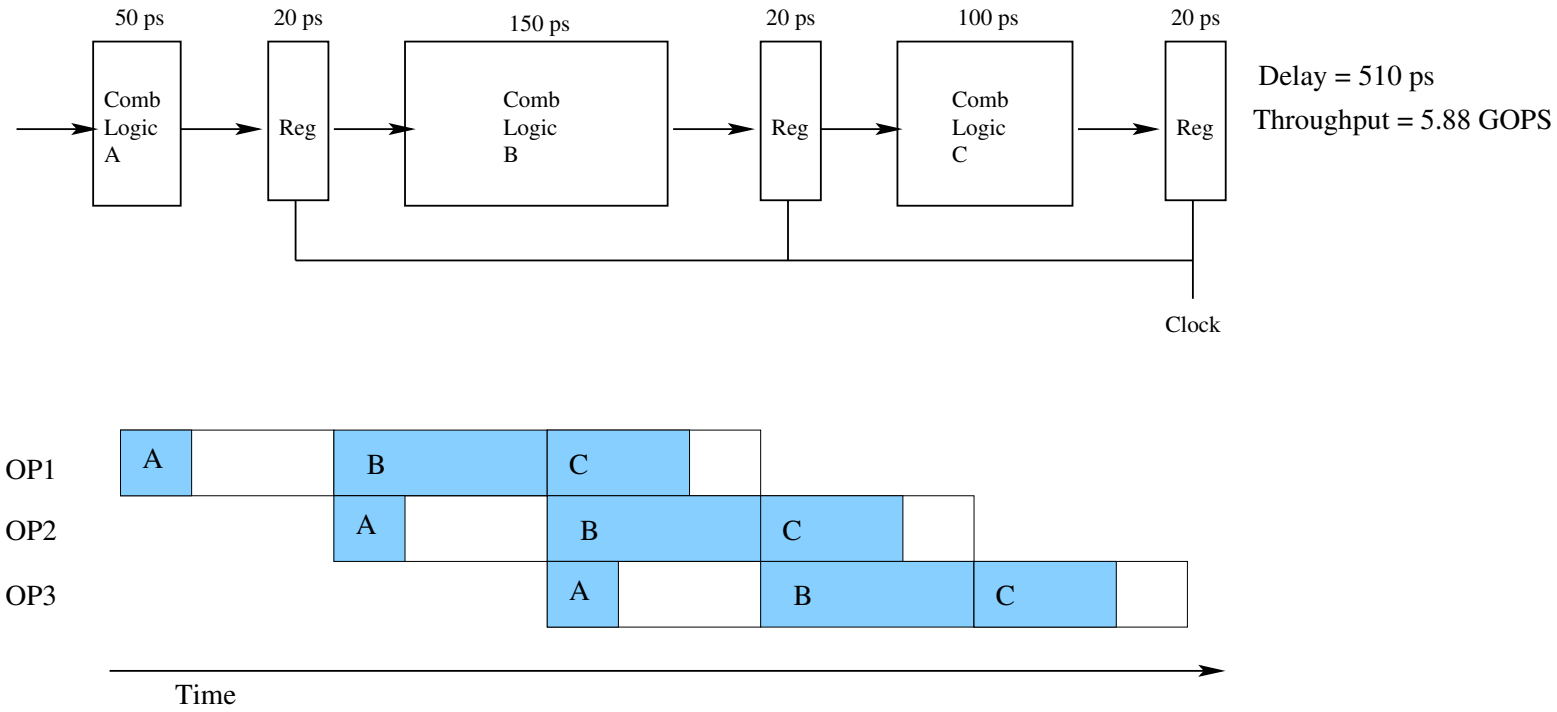
Operating a Pipeline



At times [240..260].

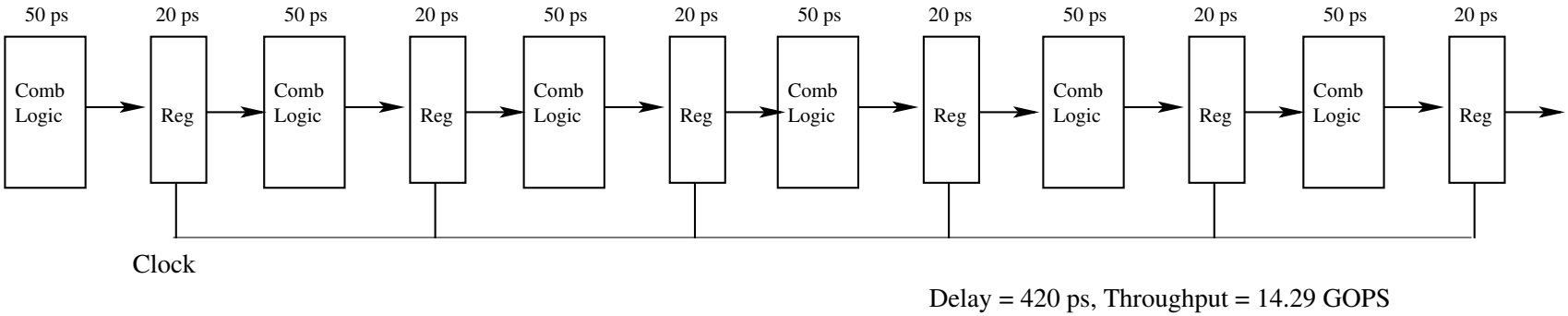


Limitations: Non-uniform Delays



- Throughput is limited by the slowest stage.
- Other stages may sit idle for much of the time.
- It's challenging to partition the system into balanced stages.

Limitations: Register Overhead



As you try to deepen the pipeline, the overhead of loading registers becomes more significant.

Percentage of clock cycle spend loading registers:

1-stage pipeline:	6.25%
3-stage pipeline:	16.67%
6-stage pipeline:	28.57%

High speeds of modern processor designs are obtained through very deep pipelining.

The Performance Equation

$$\text{CPU Time} = \frac{Seconds}{Program} = \frac{Instructions}{Program} * \frac{Cycles}{Instruction} * \frac{Seconds}{Cycle}$$

Clock Cycle Time

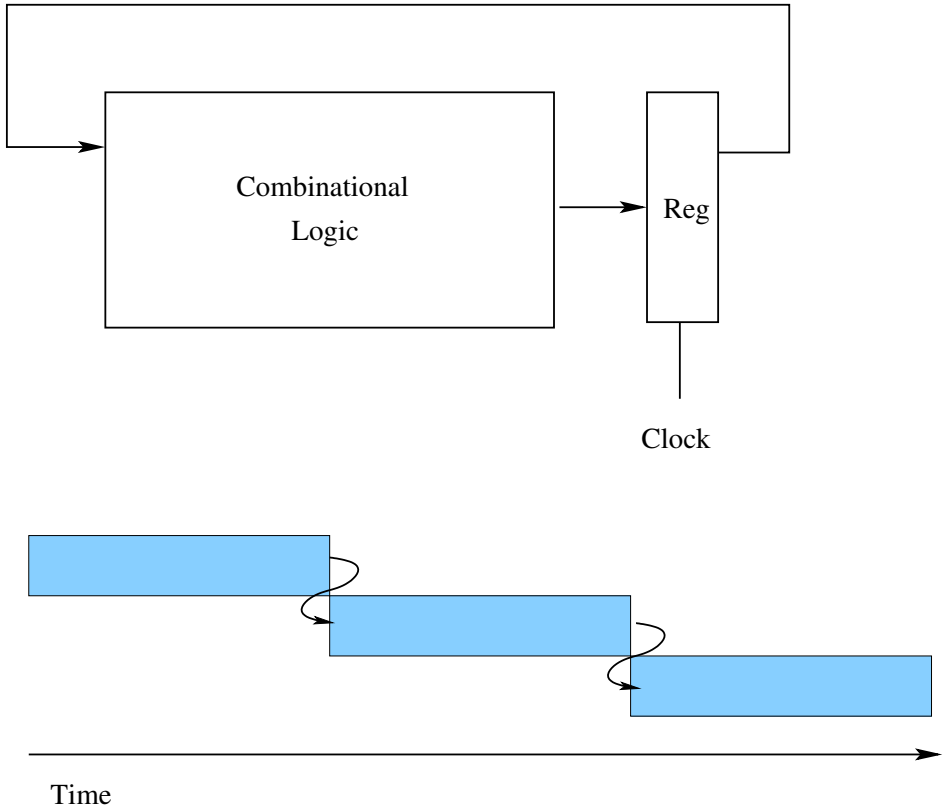
- Improves by a factor of almost N for N-deep pipeline.
- Not quite a factor of N due to pipeline overheads.

Cycles Per Instructions

- In an ideal world, CPI would stay the same.
- An individual instruction takes N cycles.
- But we have N instructions in flight at a time.
- So, average $CPI_{pipe} = (CPI_{no-pipe} * N)/N$

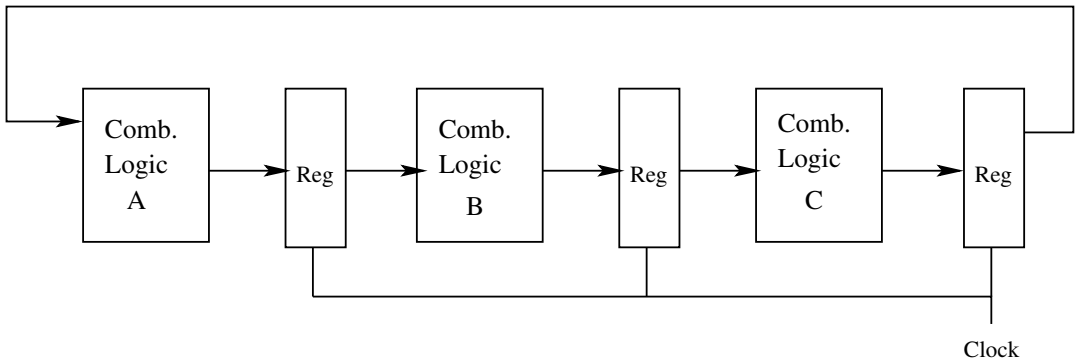
Thus, performance can improve by up to a factor of N.

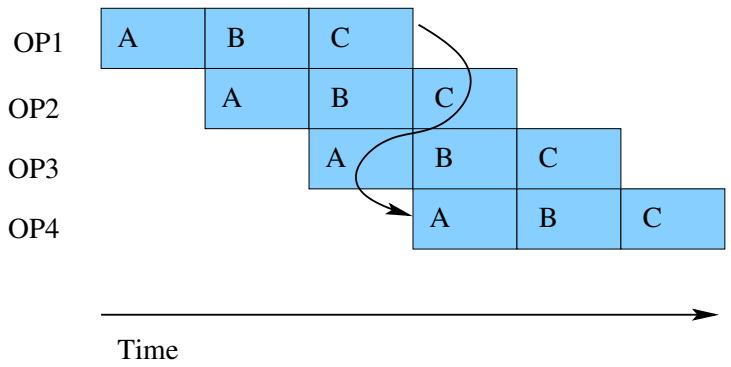
Data Dependencies



Sequential System: Each operation depends on the previous one.

Data Hazards

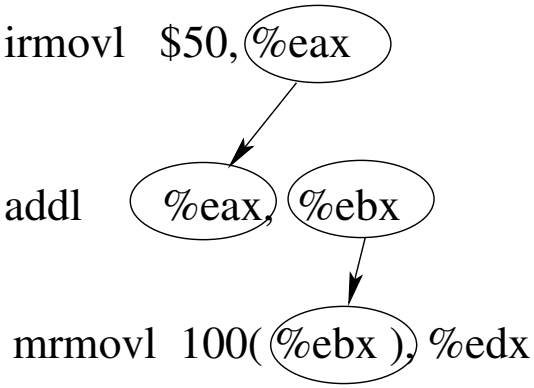




Pipelined System:

- Result does not feed back around in time for the next operation.
- Pipelining has changed the behavior of the system.

Data Dependencies in Processors

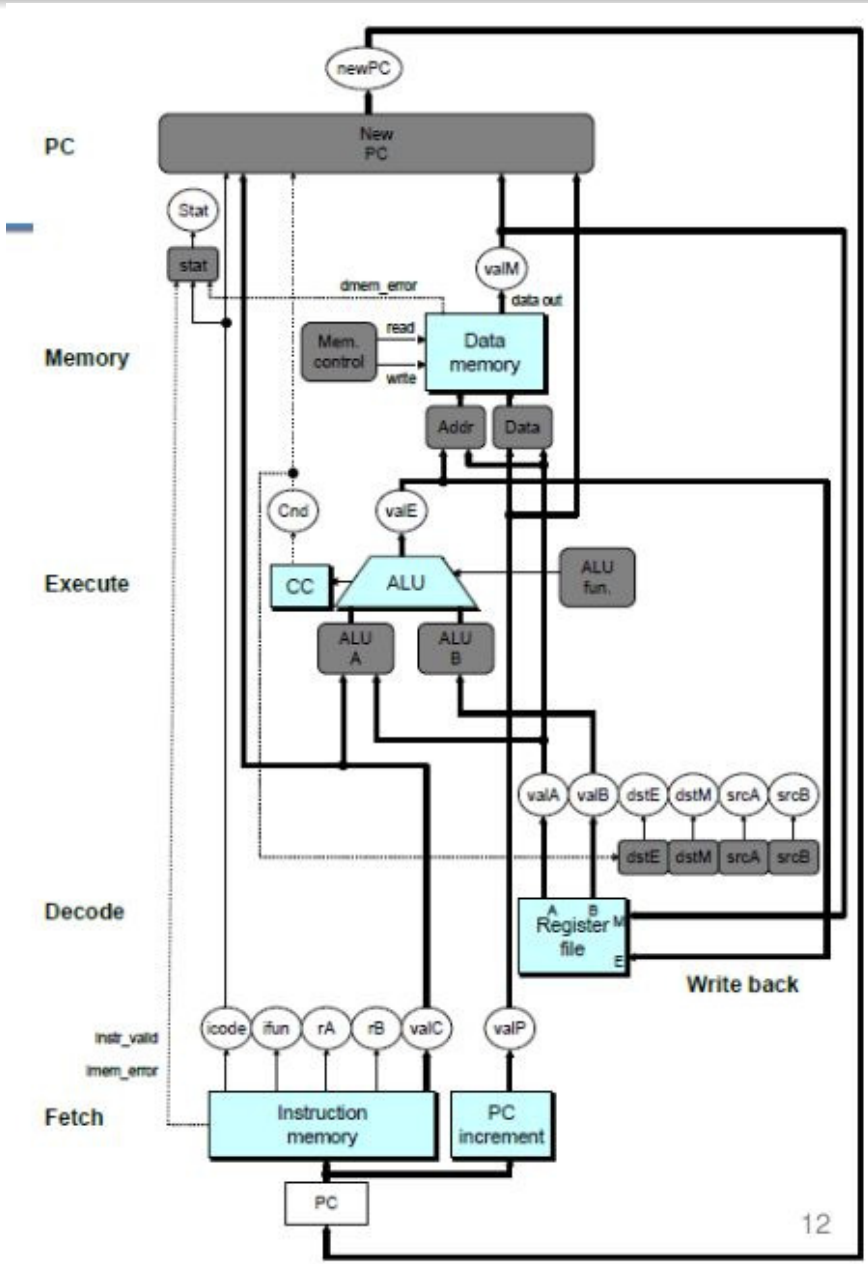


Result from one instruction is used as an operand for another; called read-after-write (RAW) dependency.

- This is very common in actual programs.
- Must make sure that our pipeline handles these properly and gets the right result.
- Should minimize performance impact as much as possible.

SEQ Hardware

- Stages occur in sequence.
- One operation in process at at time.
- One stage for each logical pipeline operation.
  - **Fetch:** get next instruction from memory.
  - **Decode:** figure out what to do, and get values from regfile.
  - **Execute:** compute.
  - **Memory:** access data memory if needed.
  - **Write back:** write results to regfile, if needed.



SEQ+ Hardware

Still sequential implementation, but reorder PC stage to put at the beginning

PC Stage

- Task is to select PC for current instruction.
- Based on results computed by previous instruction.

Processor State

- PC is no longer stored in a register.
- But, can determine PC based on other stored information.