CPU Performance
Pipelined CPU

Hakim Weatherspoon
CS 3410, Spring 2012
Computer Science
Cornell University

See P&H Chapters 1.4 and 4.5

A Simple CPU: remaining branch instructions

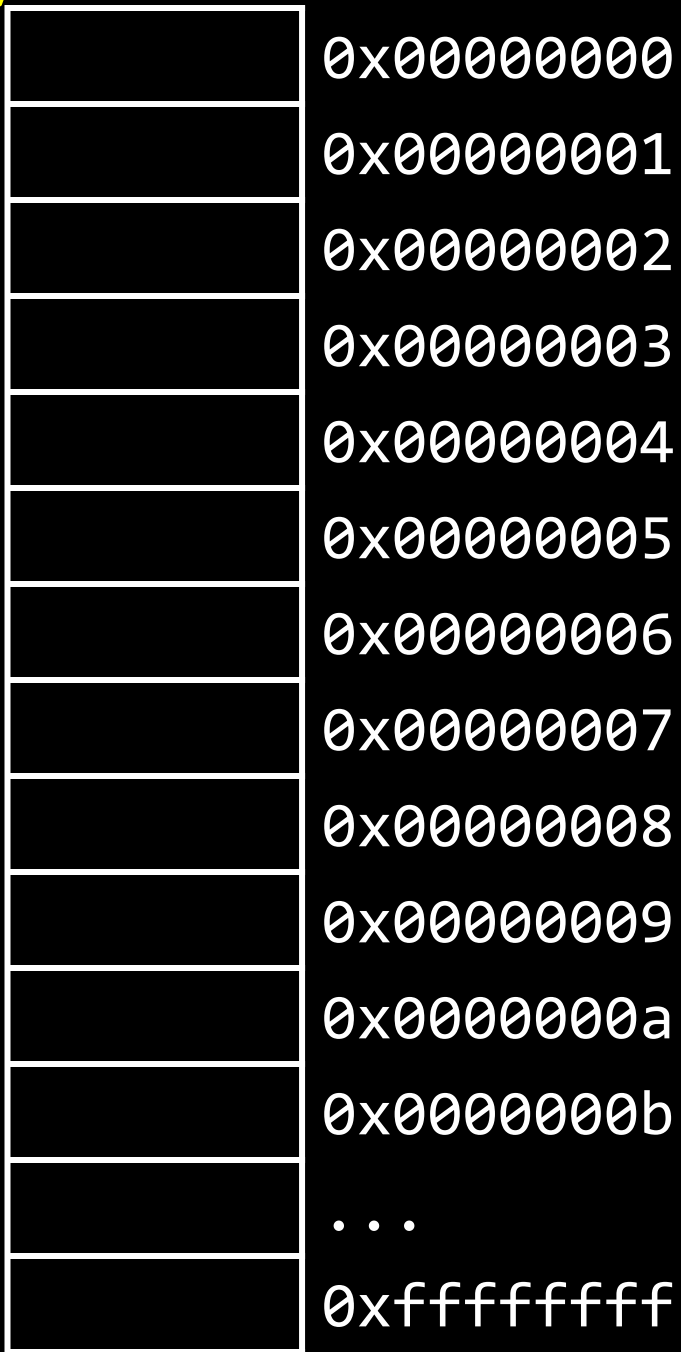
Memory Layout

Examples (big/little endian):

# r5 contains 5 (0x00000005)

```
sb r5, 2(r0)
lb r6, 2(r0)


sw r5, 8(r0)
lb r7, 8(r0)
lb r8, 11(r0)
```



Control Flow: More Branches

Conditional Jumps (cont.)

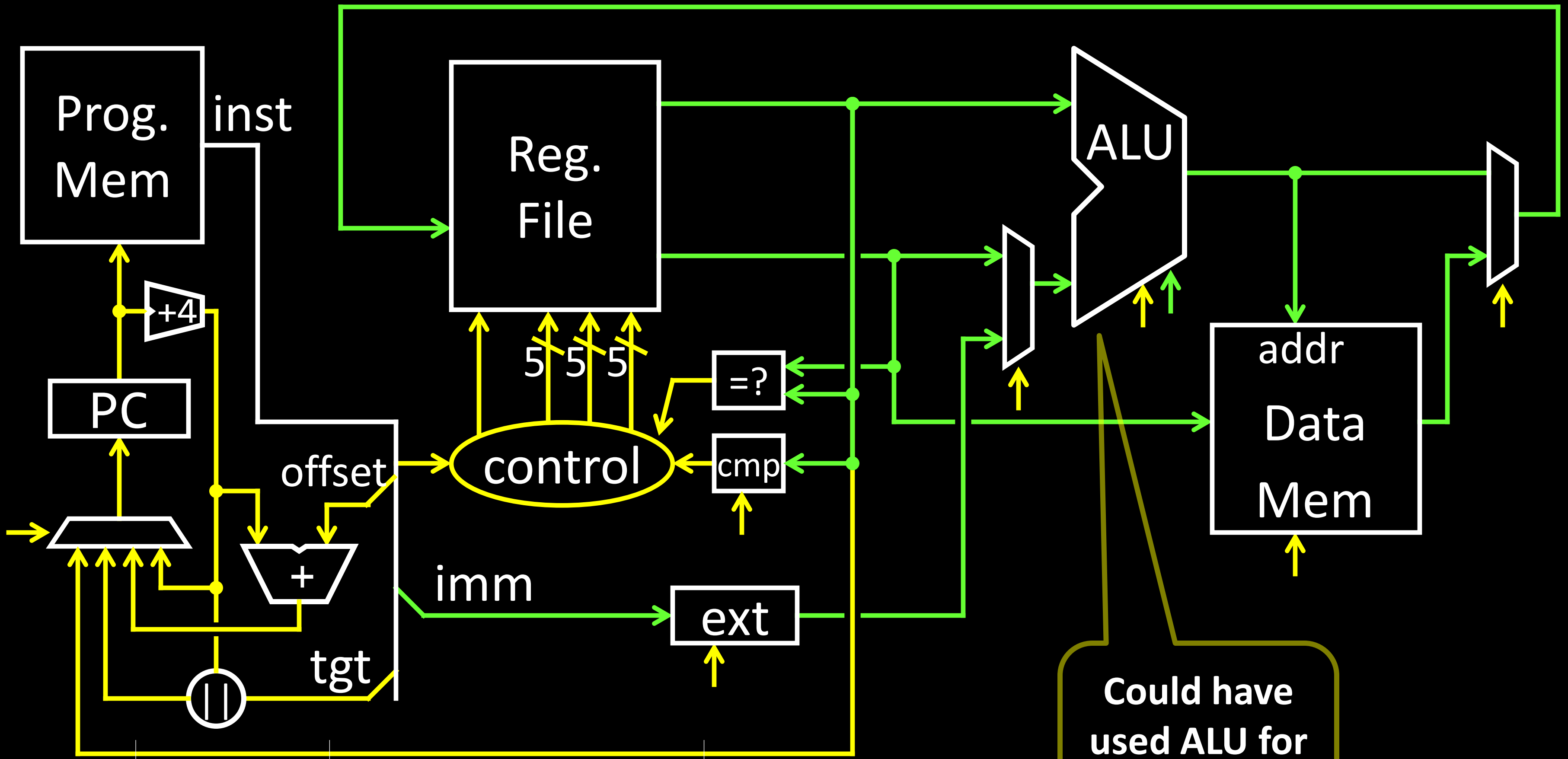
$$\underbrace{000001}_{\substack{\text{op}\\ \text{6 bits}}}\underbrace{00101}_{\substack{\text{rs}\\ \text{5 bits}}}\underbrace{00001}_{\substack{\text{subop}\\ \text{5 bits}}}\underbrace{0000000000000010}_{\substack{\text{offset}\\ \text{16 bits}}}$$

almost I-Type

signed offsets

op	subop	mnemonic	description
0x1	0x0	BLTZ rs, offset	if R[rs] < 0 then PC = PC+4+ (offset<<2)
0x1	0x1	BGEZ rs, offset	if R[rs] ≥ 0 then PC = PC+4+ (offset<<2)
0x6	0x0	BLEZ rs, offset	if R[rs] ≤ 0 then PC = PC+4+ (offset<<2)
0x7	0x0	BGTZ rs, offset	if R[rs] > 0 then PC = PC+4+ (offset<<2)

Absolute Jump



Could have used ALU for branch cmp

op	subop	mnemonic	description
0x1	0x0	BLTZ rs, offset	if R[rs] < 0 then PC = PC+4+ (offset<<2)
0x1	0x1	BGEZ rs, offset	if R[rs] ≥ 0 then PC = PC+4+ (offset<<2)
0x6	0x0	BLEZ rs, offset	if R[rs] ≤ 0 then PC = PC+4+ (offset<<2)
0x7	0x0	BGTZ rs, offset	if R[rs] > 0 then PC = PC+4+ (offset<<2)

Control Flow: Jump and Link

Function/procedure calls

$$\underbrace{000011}_{\text{op}}\underbrace{00000001001000011000000010}_{\text{immediate}}$$

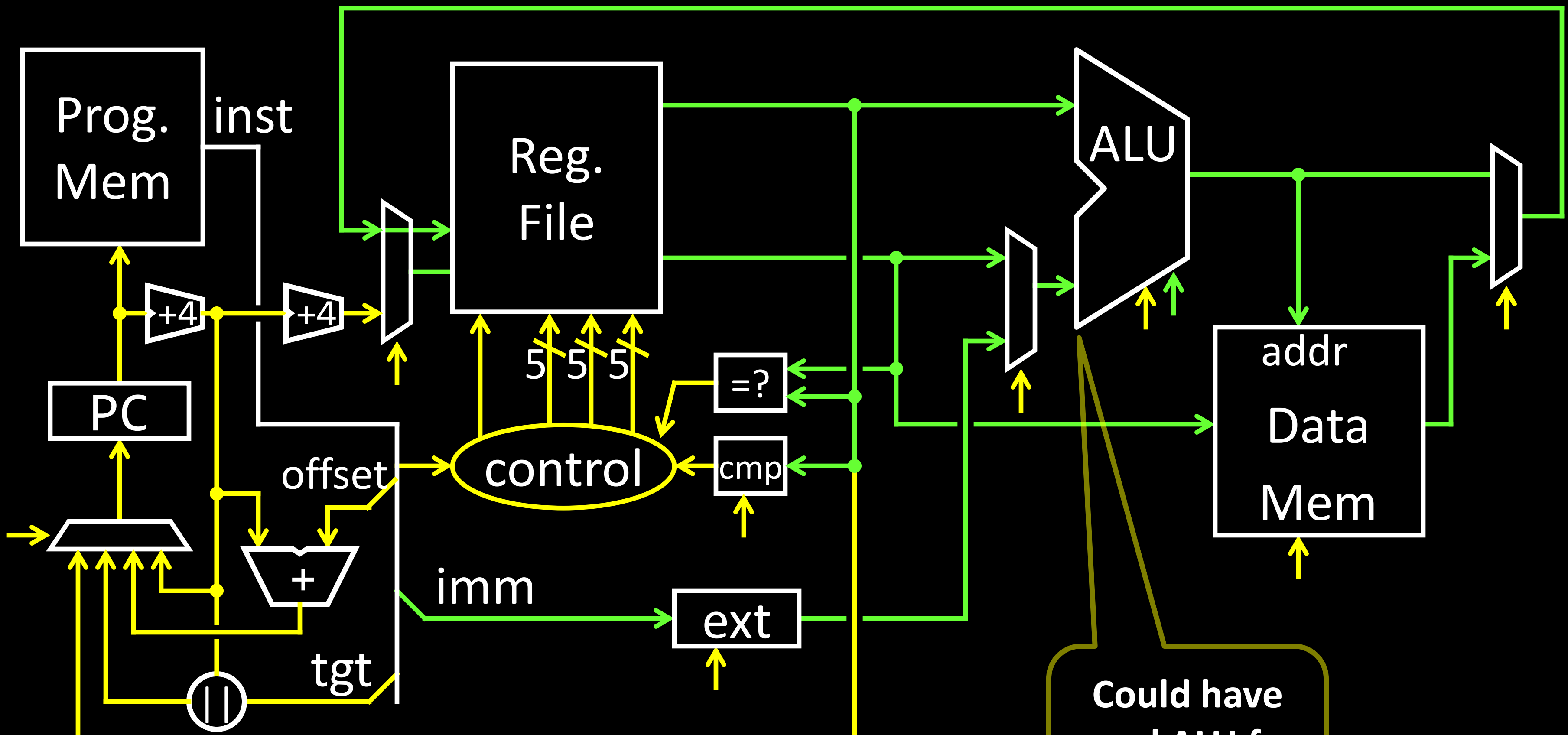
op	immediate
6 bits	26 bits

J-Type

op	mnemonic	description
0x3	JAL target	r31 = PC+8 (+8 due to branch delay slot) PC = $(PC+4)_{31..28}$ || (target << 2)

op	mnemonic	description
0x2	J target	PC = $(PC+4)_{31..28}$ || (target << 2)

Absolute Jump



Could have used ALU for link add

op	mnemonic	description
0x3	JAL target	r31 = PC+8 (+8 due to branch delay slot) PC = $(PC+4)_{31..28}$ || (target << 2)

Performance

See: P&H 1.4

Design Goals

What to look for in a computer system?

- Correctness: negotiable?
- Cost
  - purchase cost = f(silicon size = gate count, economics)
  - operating cost = f(energy, cooling)
  - operating cost >= purchase cost
- Efficiency
  - power = f(transistor usage, voltage, wire size, clock rate, …)
  - heat = f(power)
    - Intel Core i7 Bloomfield: 130 Watts
    - AMD Turion: 35 Watts
    - Intel Core 2 Solo: 5.5 Watts
    - Cortex-A9 Dual Core @800MHz: 0.4 Watts
- Performance
- Other: availability, size, greenness, features, …

Performance

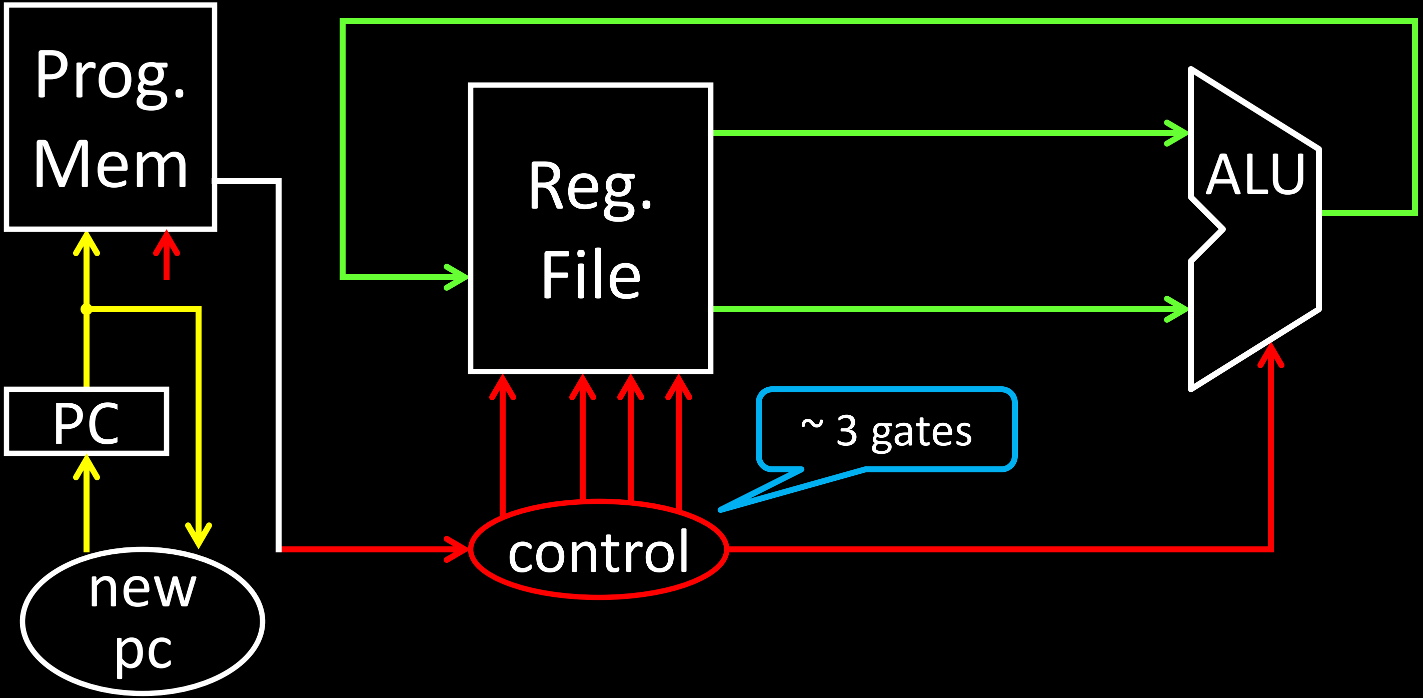
How to measure performance?

- GHz (billions of cycles per second)
- MIPS (millions of instructions per second)
- MFLOPS (millions of floating point operations per second)
- benchmarks (SPEC, TPC, …)

Metrics

- latency: how long to finish my program
- throughput: how much work finished per unit time

How Fast?



Assumptions:

- alu: 32 bit ripple carry + some muxes
- next PC: 30 bit ripple carry
- control: minimized for delay (~3 gates)
- transistors: 2 ns per gate
- prog,. memory: 16 ns (as much as 8 gates)
- register file: 2 ns access
- ignore wires, register setup time

Better:

- alu: 32 bit carry lookahead + some muxes (~ 9 gates)
- next PC: 30 bit carry lookahead (~ 6 gates)

Better Still:

- next PC: cheapest adder faster than 21 gate delays

All signals are stable

- 80 gates => clock period of at least 160 ns, max frequency ~6MHz

Better:

- 21 gates => clock period of at least 42 ns, max frequency ~24MHz

Adder Performance

32 Bit Adder Design	Space	Time
Ripple Carry	≈ 300 gates	≈ 64 gate delays
2-Way Carry-Skip	≈ 360 gates	≈ 35 gate delays
3-Way Carry-Skip	≈ 500 gates	≈ 22 gate delays
4-Way Carry-Skip	≈ 600 gates	≈ 18 gate delays
2-Way Look-Ahead	≈ 550 gates	≈ 16 gate delays
Split Look-Ahead	≈ 800 gates	≈ 10 gate delays
Full Look-Ahead	≈ 1200 gates	≈ 5 gate delays

Optimization: Summary

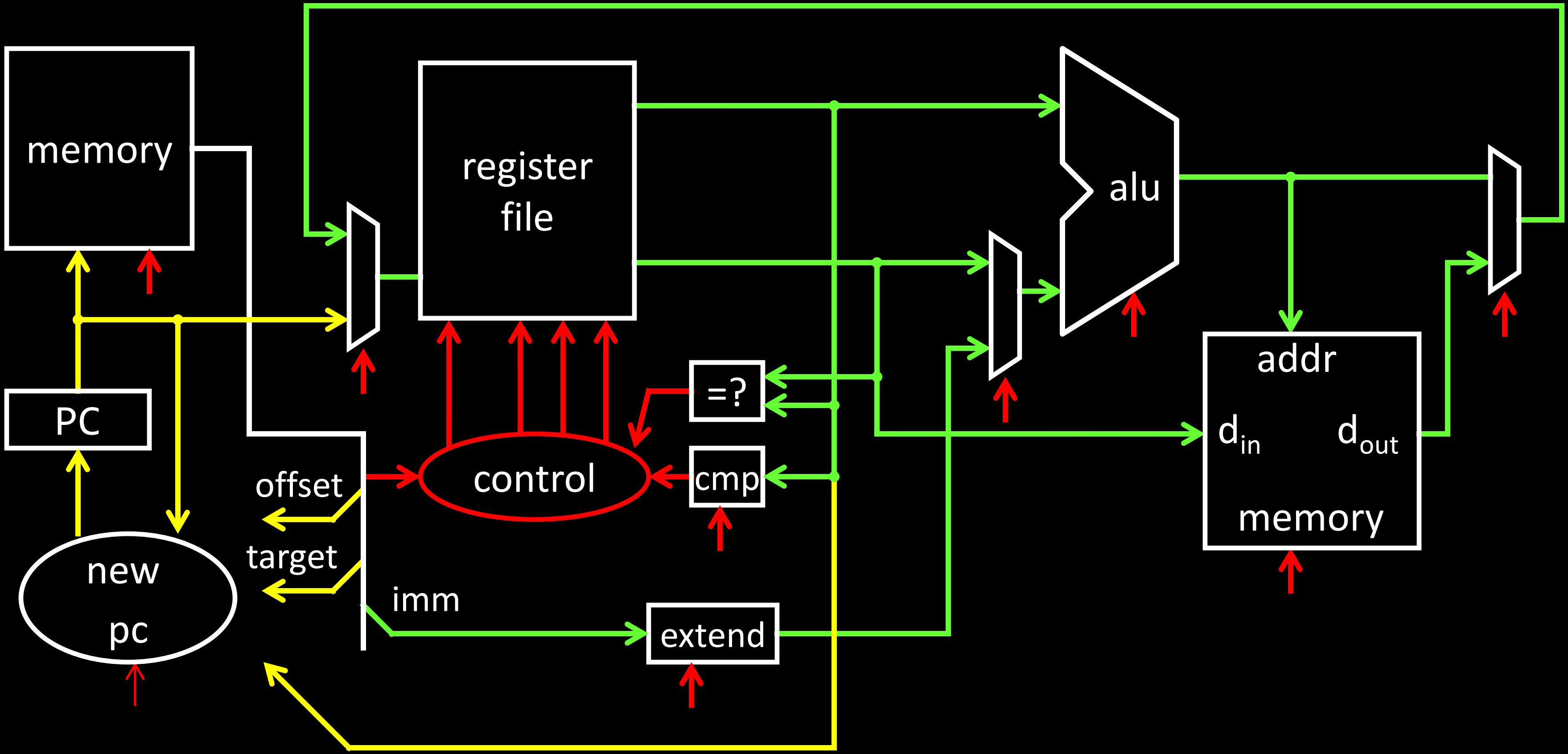
Critical Path

- Longest path from a register output to a register input
- Determines minimum cycle, maximum clock frequency

Strategy 1 (we just employed)

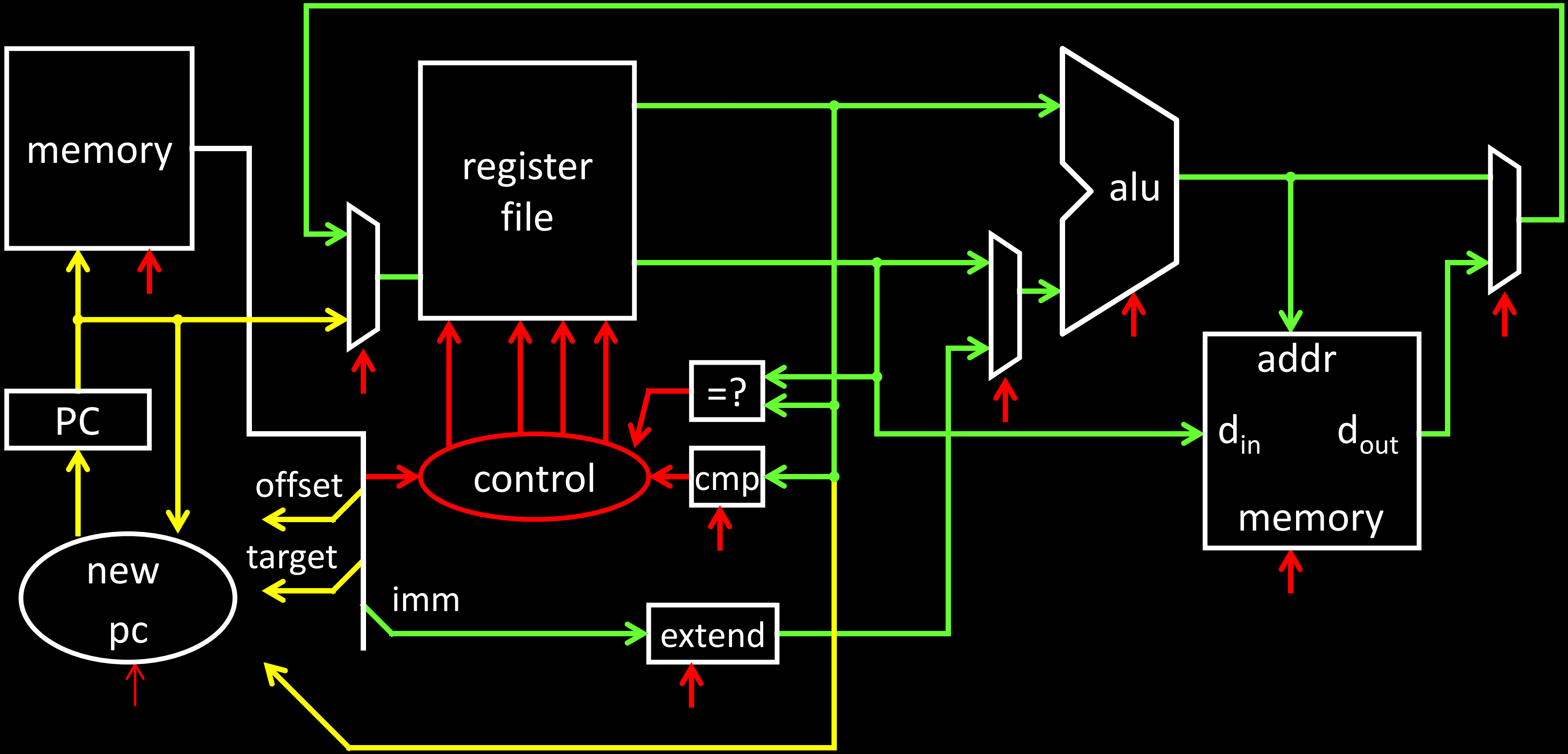
- Optimize for delay on the critical path
- Optimize for size / power / simplicity elsewhere
  - next PC

Processor Clock Cycle



op	mnemonic	description
0x20	LB rd, offset(rs)	R[rd] = sign_ext(Mem[offset+R[rs]])
0x23	LW rd, offset(rs)	R[rd] = Mem[offset+R[rs]]
0x28	SB rd, offset(rs)	Mem[offset+R[rs]] = R[rd]
0x2b	SW rd, offset(rs)	Mem[offset+R[rs]] = R[rd]

Processor Clock Cycle



op	func	mnemonic	description
0x0	0x08	JR rs	PC = R[rs]

op	mnemonic	description
0x2	J target	PC = $(PC+4)_{31..28}$ || (target << 2)

Multi-Cycle Instructions

Strategy 2

- Multiple cycles to complete a single instruction

E.g: Assume:

- load/store: 100 ns
- arithmetic: 50 ns
- branches: 33 ns

Multi-Cycle CPU

30 MHz (33 ns cycle) with

- 3 cycles per load/store
- 2 cycles per arithmetic
- 1 cycle per branch

Faster than Single-Cycle CPU?

10 MHz (100 ns cycle) with

- 1 cycle per instruction

CPI

Instruction mix for some program P, assume:

- 25% load/store (3 cycles / instruction)
- 60% arithmetic (2 cycles / instruction)
- 15% branches (1 cycle / instruction)

Multi-Cycle performance for program P:

$3 * .25 + 2 * .60 + 1 * .15 = 2.1$

average *cycles per instruction* (CPI) = 2.1

Multi-Cycle @ 30 MHz
Single-Cycle @ 10 MHz
Single-Cycle @ 15 MHz

800 MHz PIII “faster” than 1 GHz P4

Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):

- 25% load/store, CPI = 3
- 60% arithmetic, CPI = 2
- 15% branches, CPI = 1

Amdahl's Law

Amdahl's Law

Execution time after improvement =

$$\frac{\text{execution time affected by improvement}}{\text{amount of improvement}} + \text{execution time unaffected}$$

Or:

Speedup is limited by popularity of improved feature

Corollary:

Make the common case fast

Caveat:

Law of diminishing returns

Pipelining

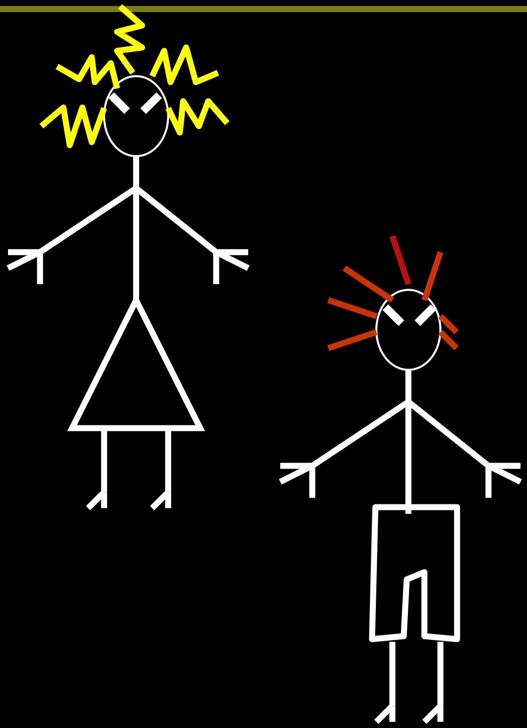
See: P&H Chapter 4.5

The Kids

Alice

Bob

They don't always get along…



The Bicycle

The Materials

Saw

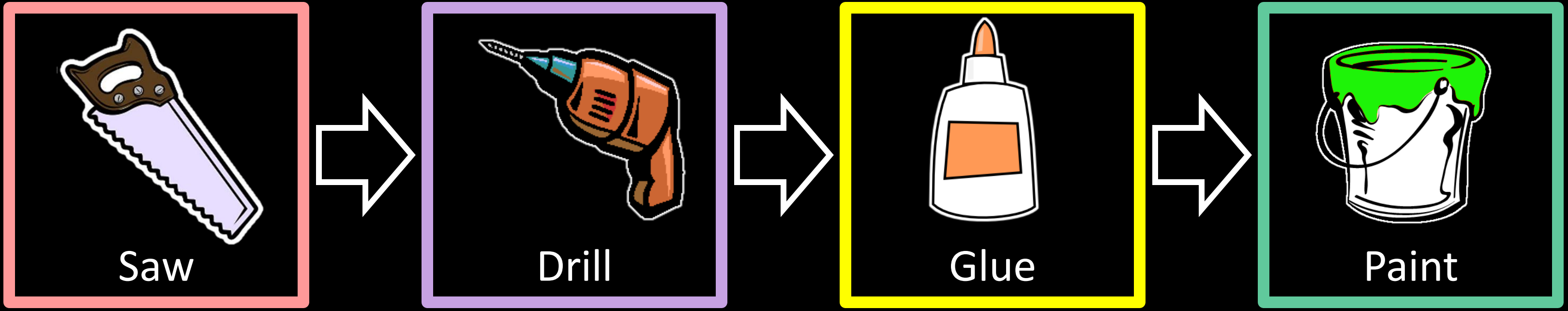
Drill

Glue

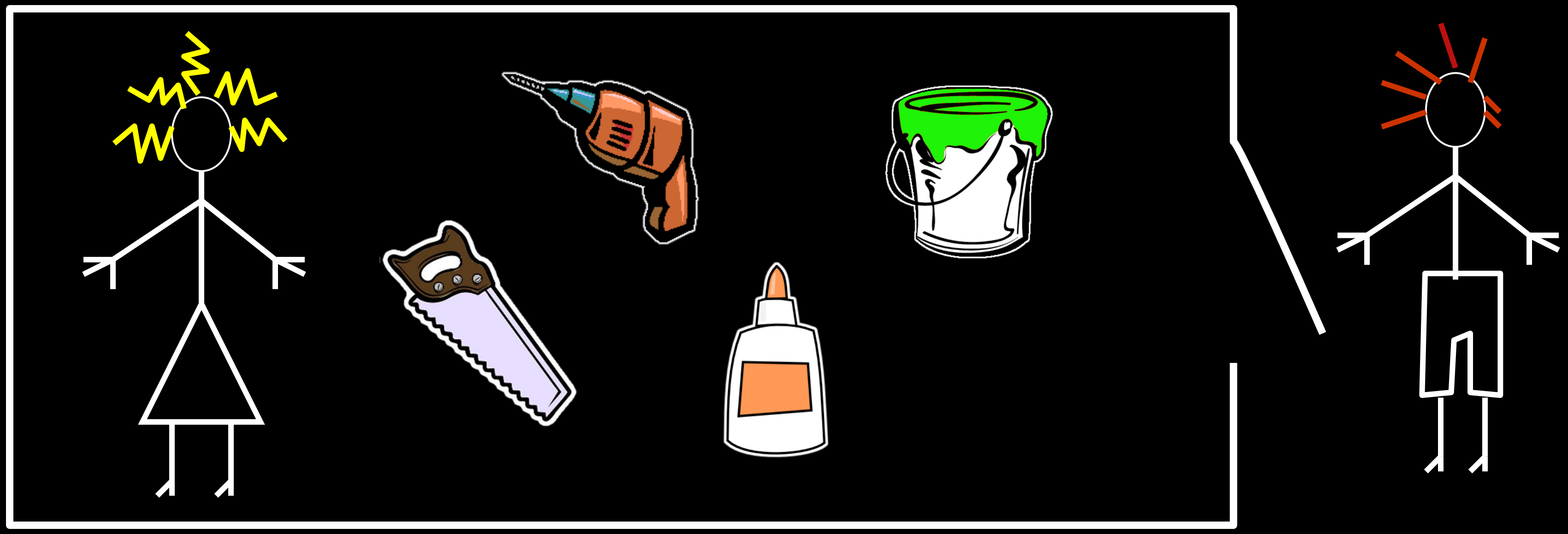
Paint

The Instructions

N pieces, each built following same sequence:



Design 1: Sequential Schedule



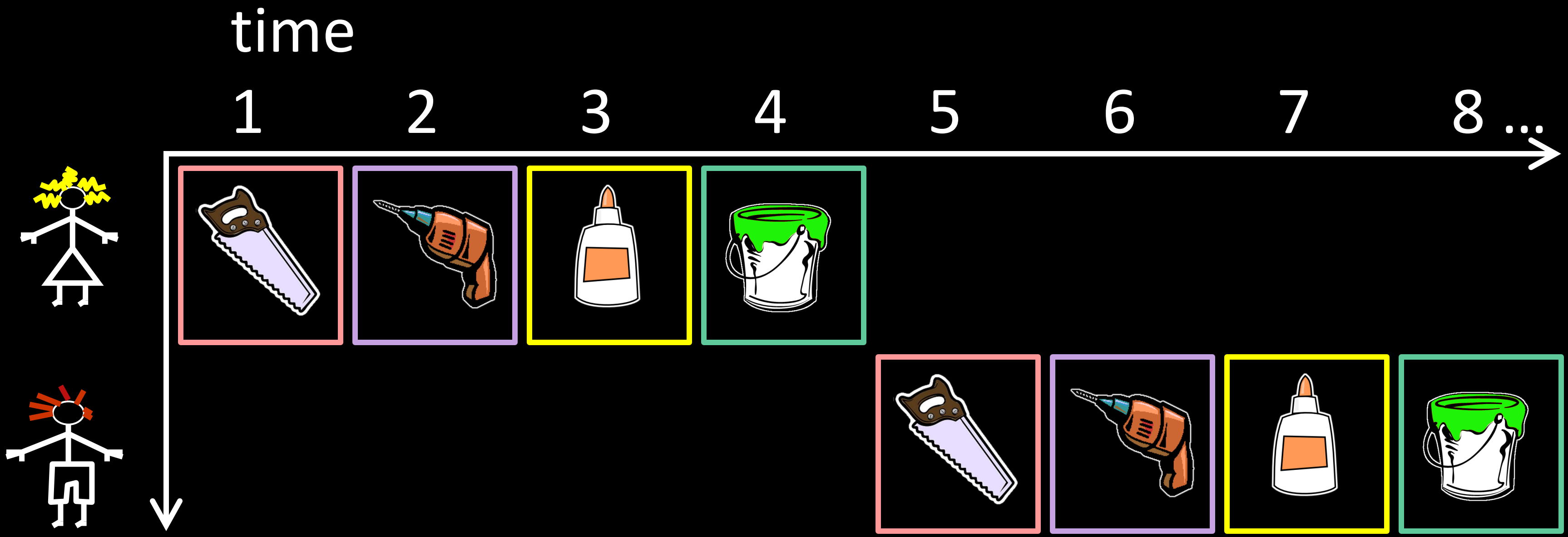
Alice owns the room

Bob can enter when Alice is finished

Repeat for remaining tasks

No possibility for conflicts

Sequential Performance



Latency:

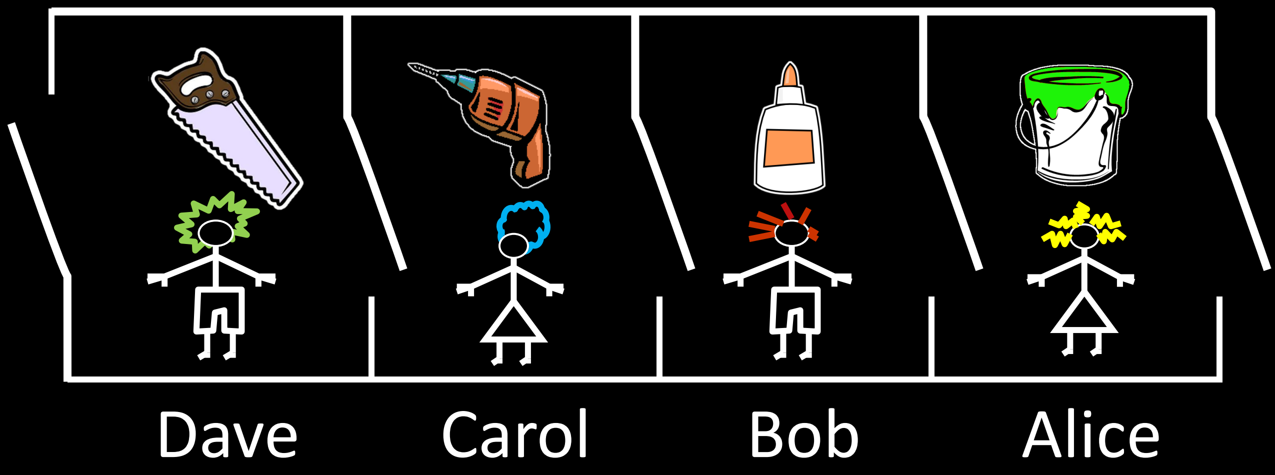
Throughput:

Concurrency:

Can we do better?

Design 2: Pipelined Design

Partition room into *stages* of a *pipeline*



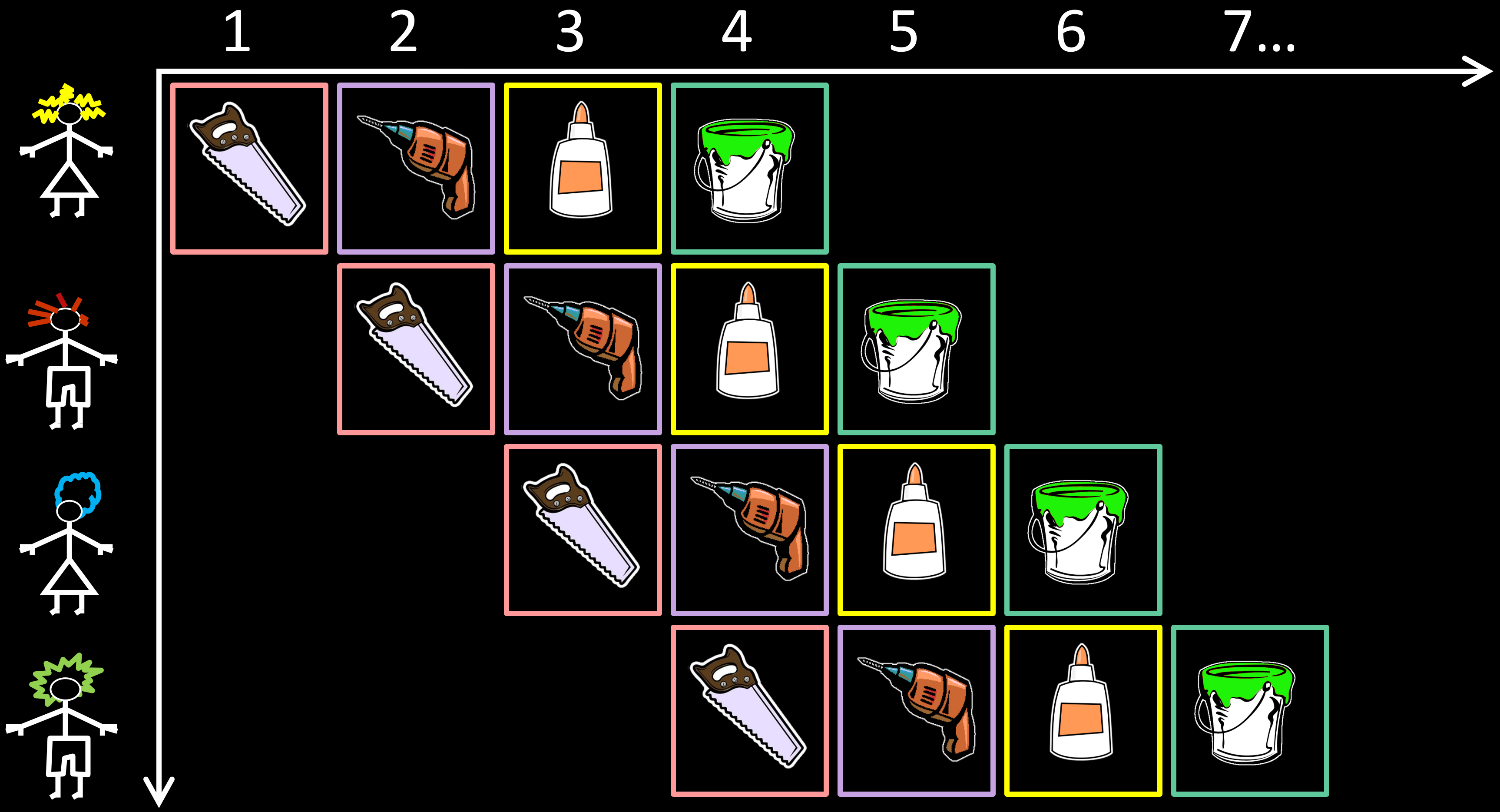
One person owns a stage at a time

4 stages

4 people working simultaneously

Everyone moves right in lockstep

Pipelined Performance

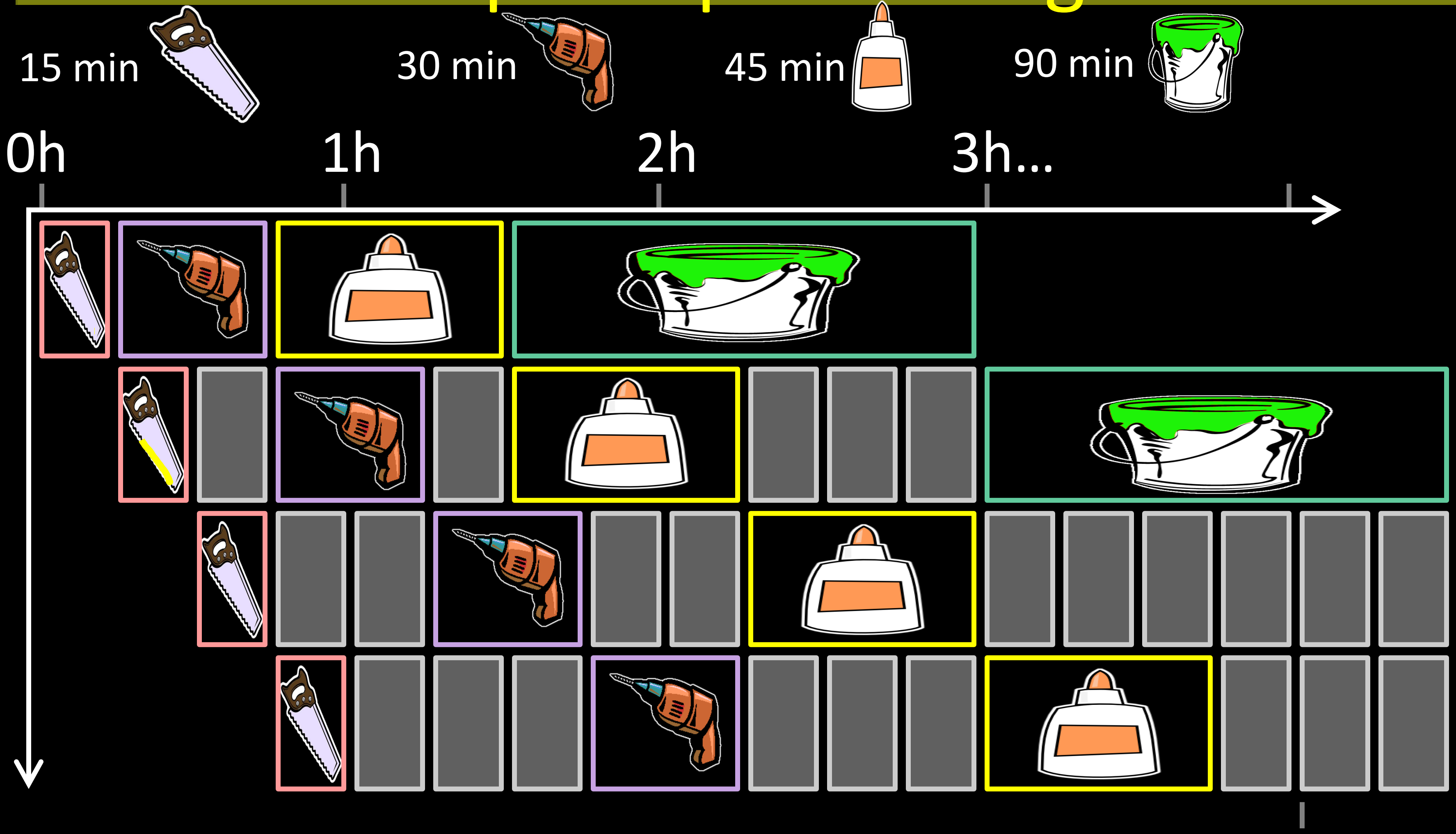


Latency:

Throughput:

Concurrency:

Unequal Pipeline Stages

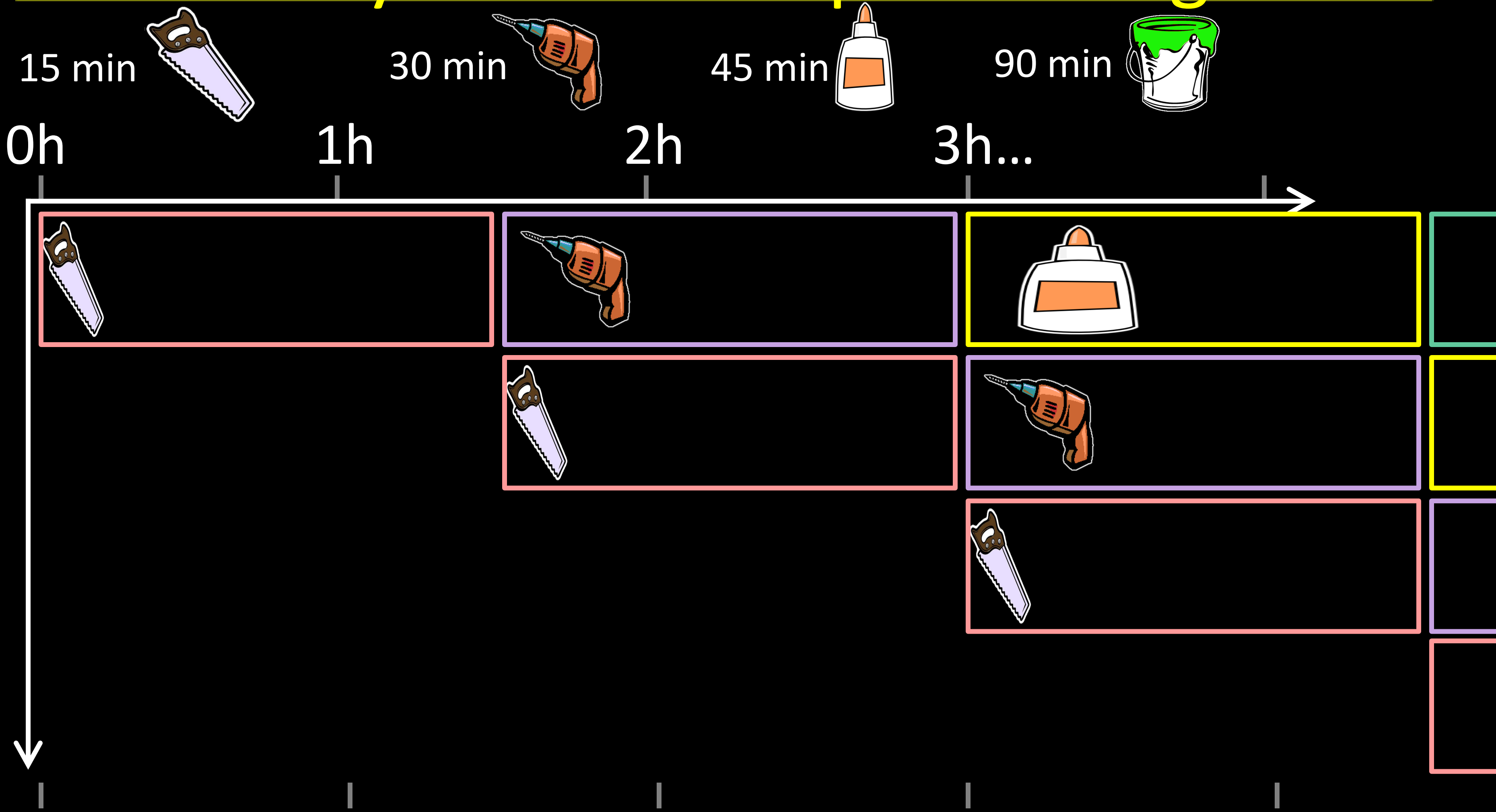


Latency:

Throughput:

Concurrency:

Poorly-balanced Pipeline Stages

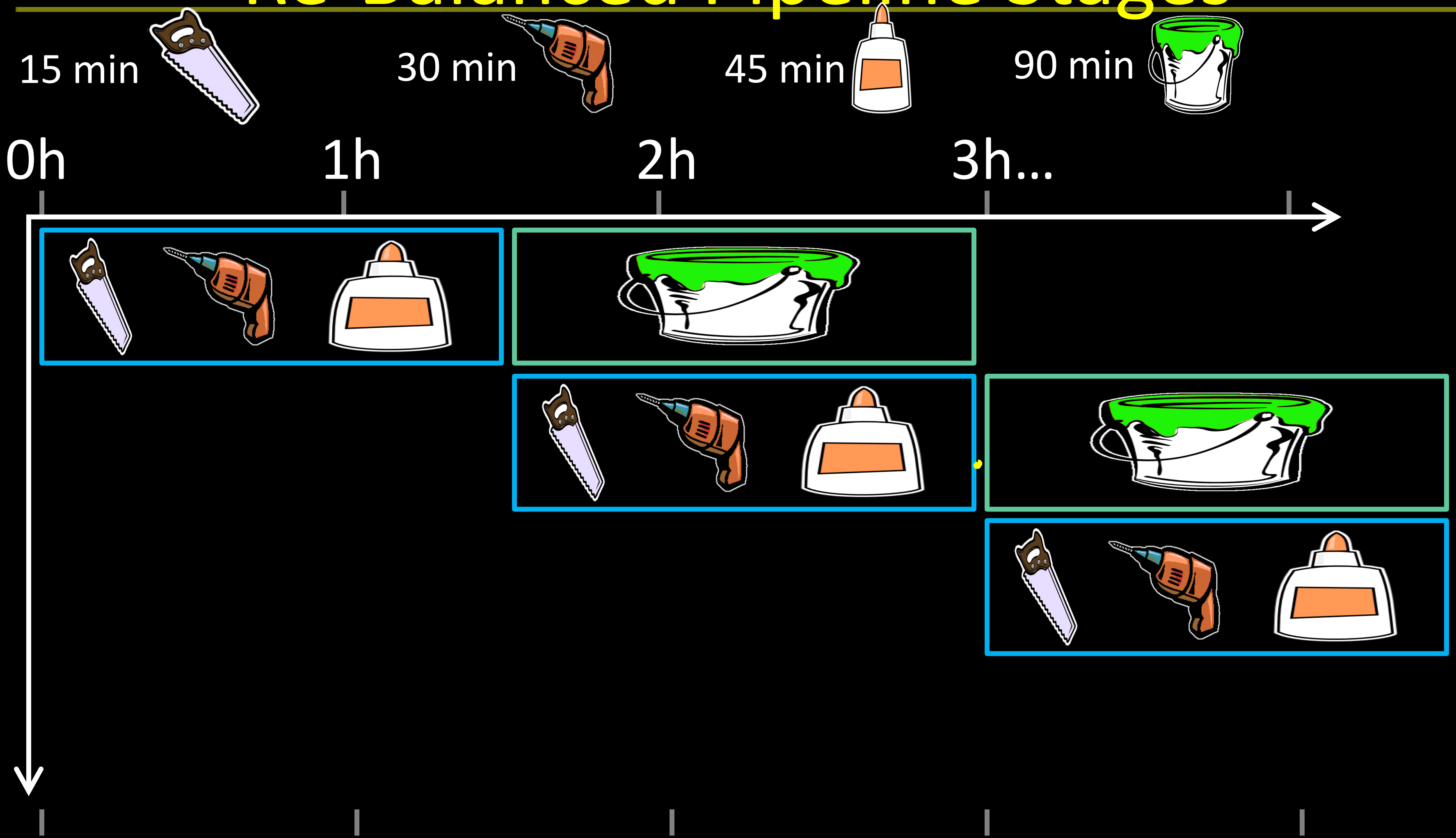


Latency:

Throughput:

Concurrency:

Re-Balanced Pipeline Stages

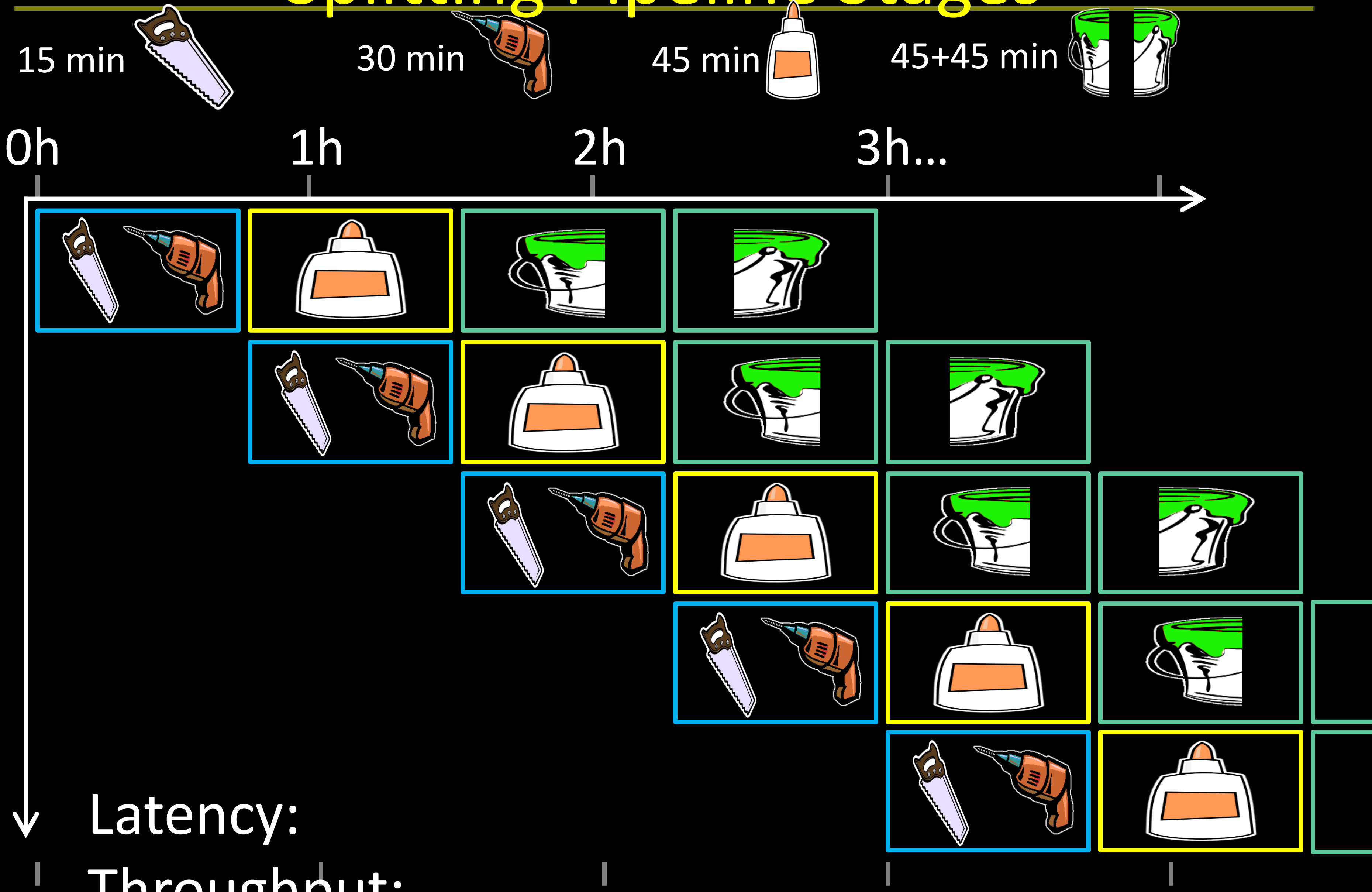


Latency:

Throughput:

Concurrency:

Splitting Pipeline Stages



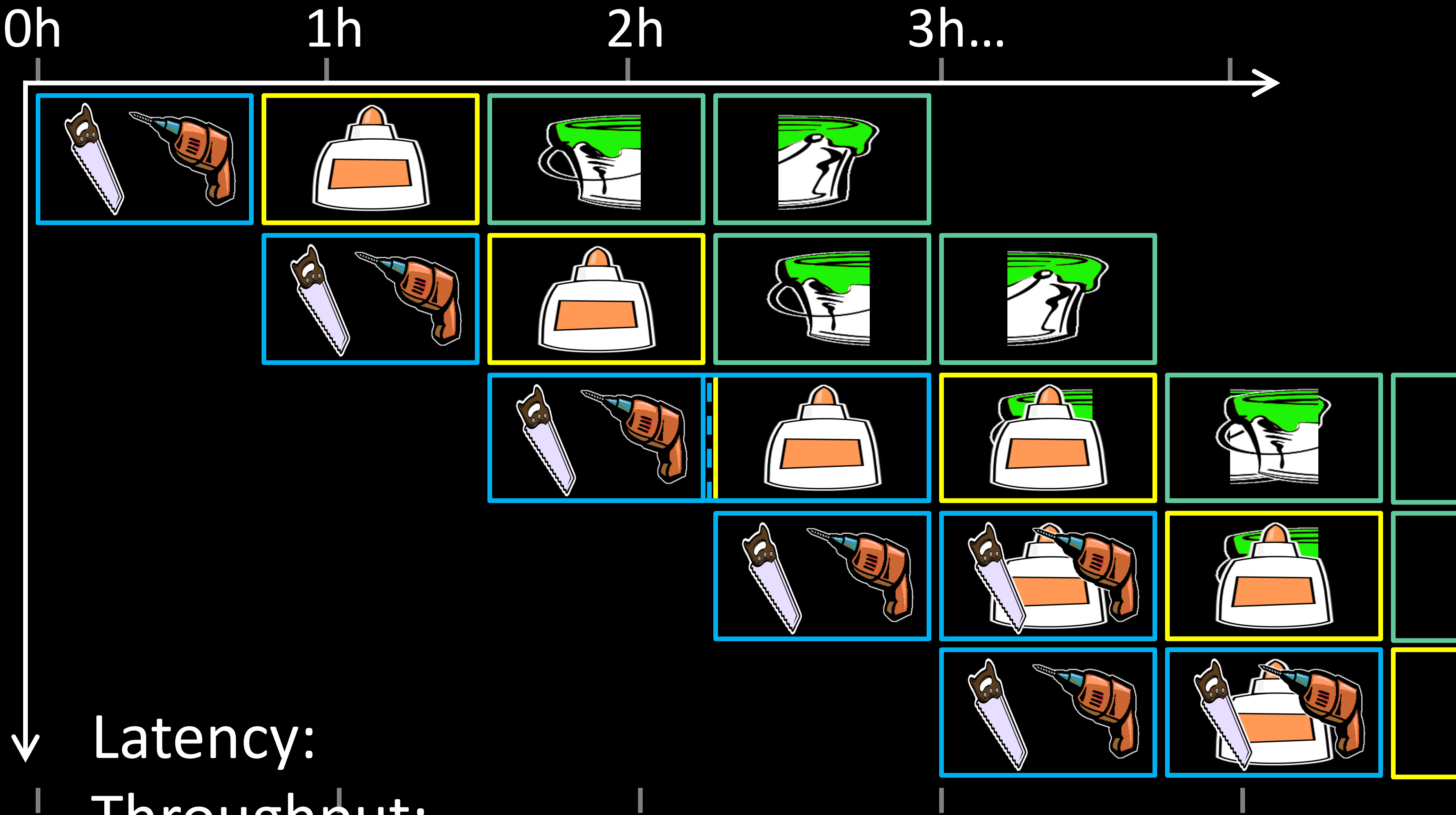
Latency:

Throughput:

Concurrency:

Pipeline Hazards

Q: What if glue step of task 3 depends on output of task 1?



Latency:

Throughput:

Concurrency:

Lessons

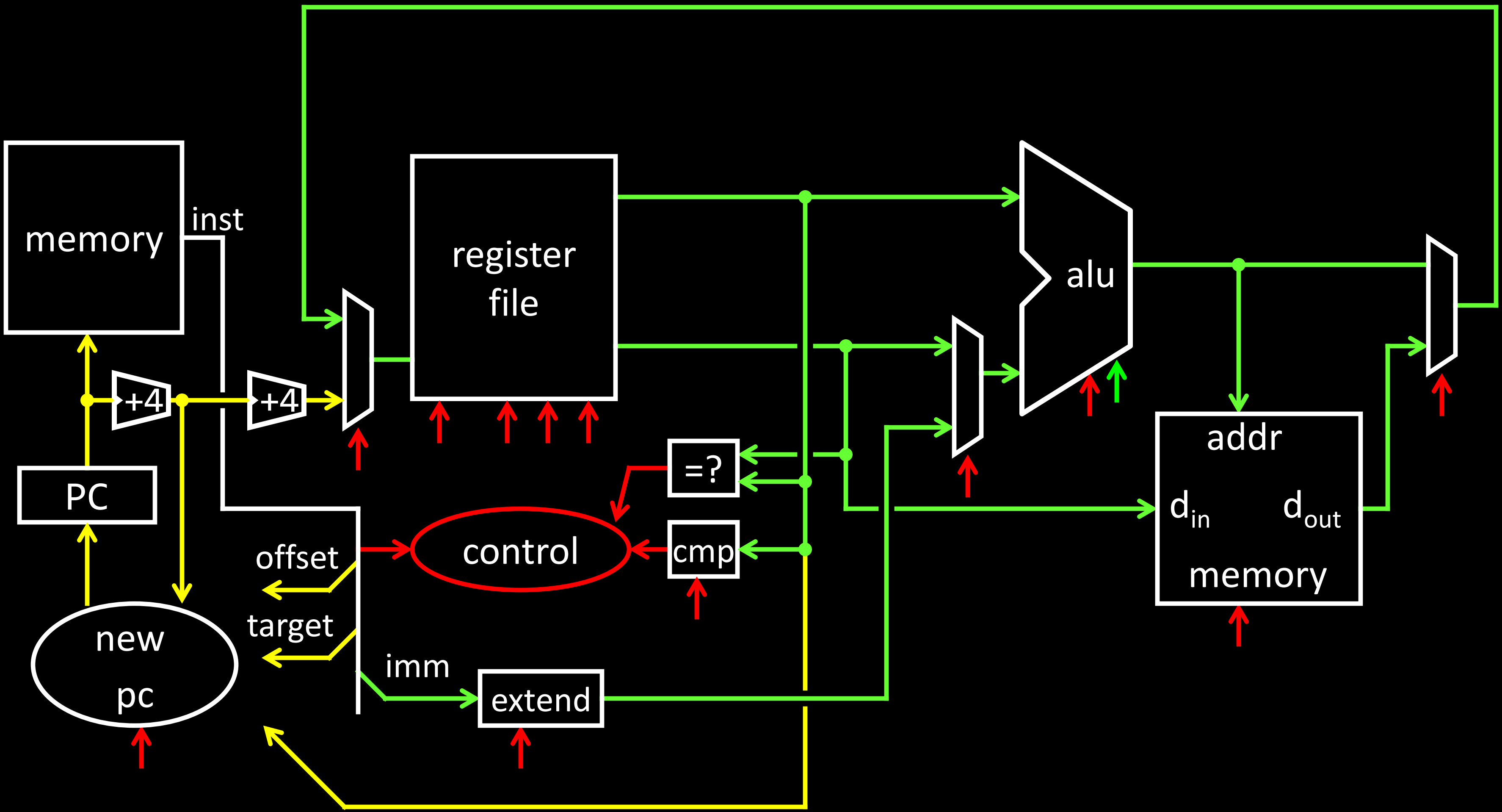
Principle:

Throughput increased by parallel execution

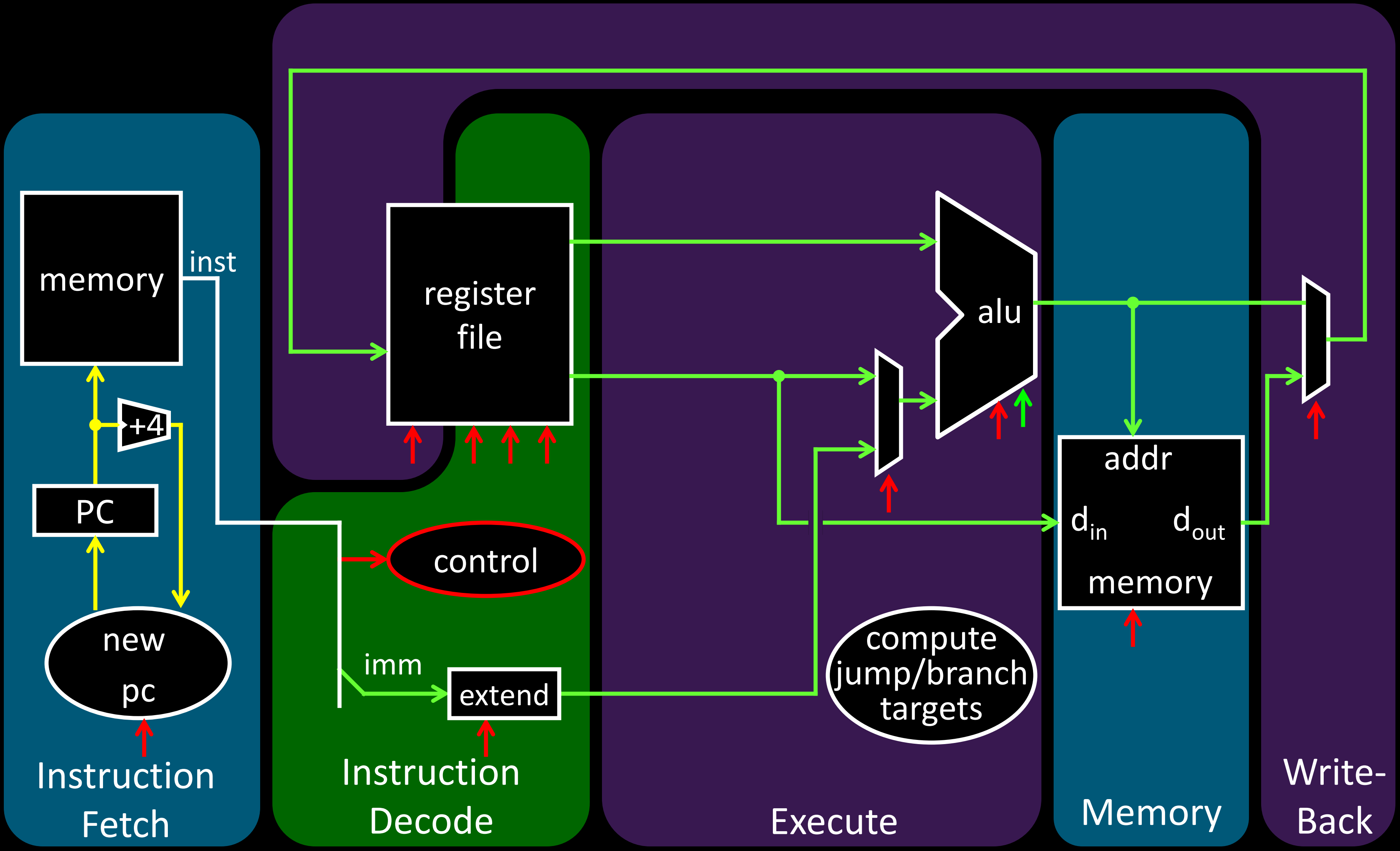
Pipelining:

- Identify *pipeline stages*
- Isolate stages from each other
- Resolve pipeline *hazards*

A Processor


memory
inst
register file
alu
+4
+4
PC
=?
control
cmp
offset
target
new pc
imm
extend
addr
d_{in}
d_{out}
memory

A Processor


memory
inst
+4
PC
new pc
register file
control
imm
extend
alu
compute jump/branch targets
addr
d_{in}
d_{out}
memory
Instruction Fetch
Instruction Decode
Execute
Memory
Write-Back

Basic Pipeline

Five stage “RISC” load-store architecture

1. Instruction fetch (IF)
   - get instruction from memory, increment PC
2. Instruction Decode (ID)
   - translate opcode into control signals and read registers
3. Execute (EX)
   - perform ALU operation, compute jump/branch targets
4. Memory (MEM)
   - access memory if needed
5. Writeback (WB)
   - update register file

Pipelined Implementation

Break instructions across multiple clock cycles (five, in this case)

Design a separate stage for the execution performed during each clock cycle

Add pipeline registers (flip-flops) to isolate signals between different stages