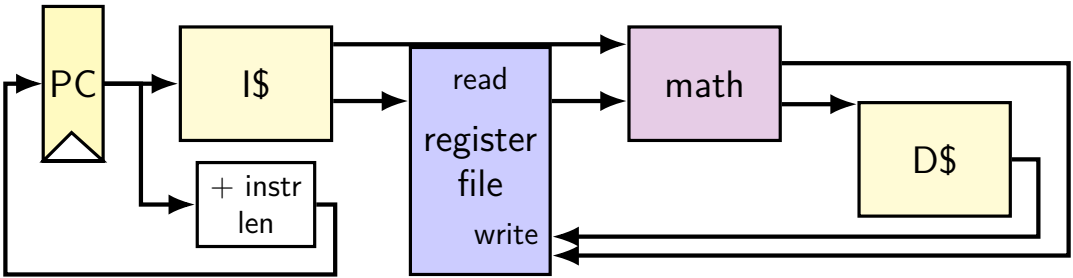
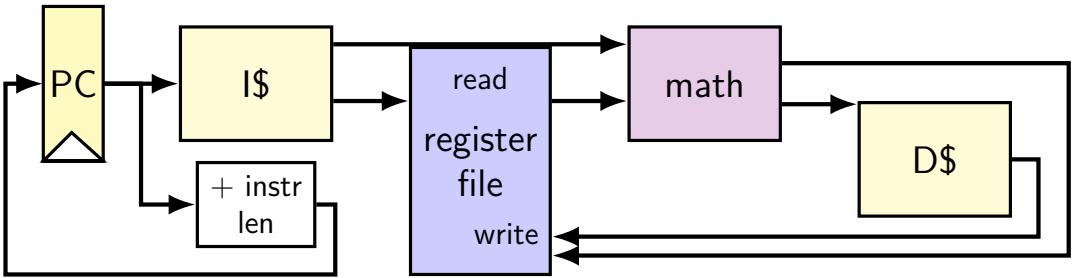
simple CPU



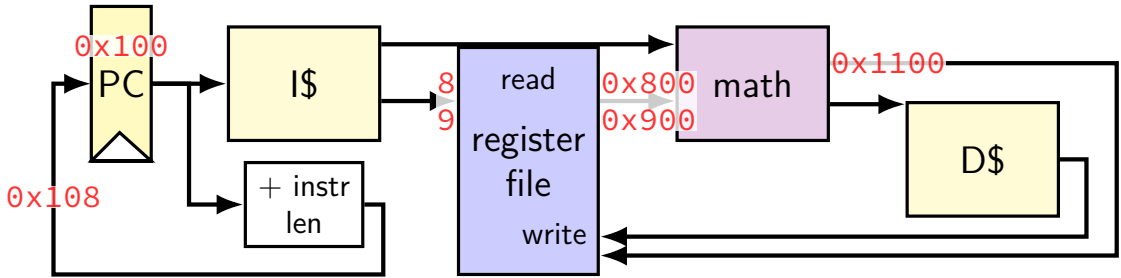
running instructions




```
0x100: addq %r8, %r9
0x108: movq 0x1234(%r10), %r11
```

```
…
%r8: 0x800
%r9: 0x900
%r10: 0x1000
%r11: 0x1100
…
```

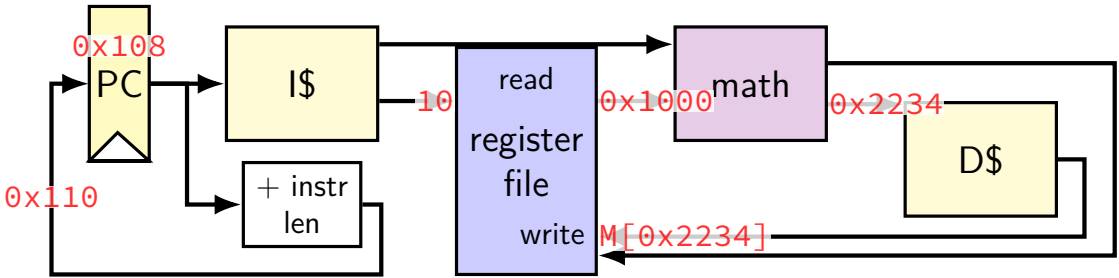
running instructions




```
0x100: addq %r8, %r9
0x108: movq 0x1234(%r10), %r11
```

```
…
%r8: 0x800
%r9: 0x1100
%r10: 0x1000
%r11: 0x1100
…
```

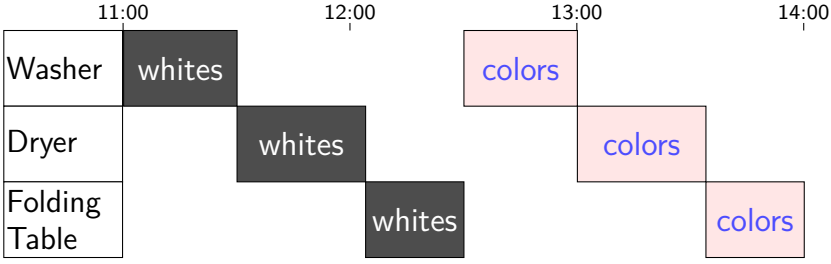
running instructions



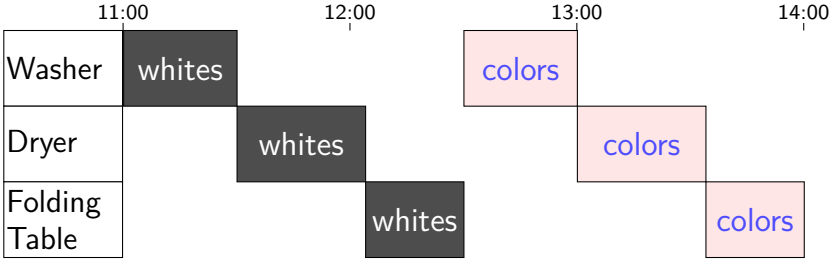

```
0x100: addq %r8, %r9
0x108: movq 0x1234(%r10), %r11
```

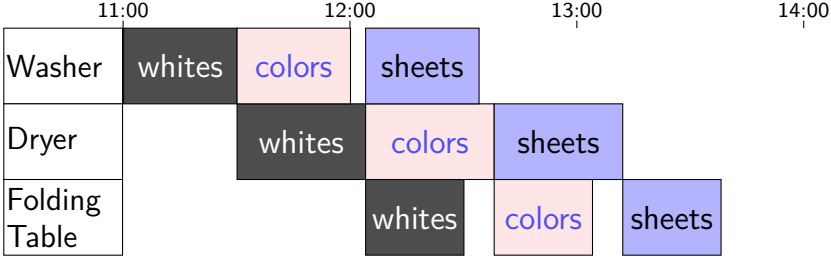
```
…
%r8: 0x800
%r9: 0x1100
%r10: 0x1000
%r11: M[0x2234]
…
```

Human pipeline: laundry

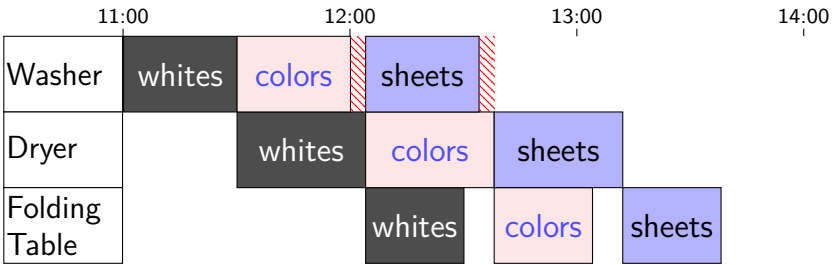


Human pipeline: laundry

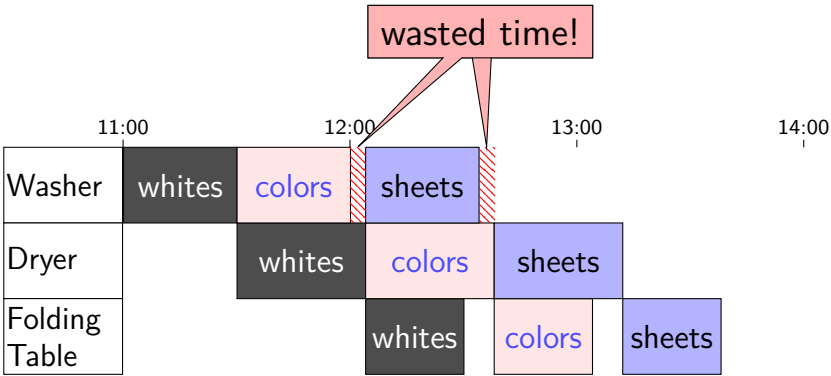




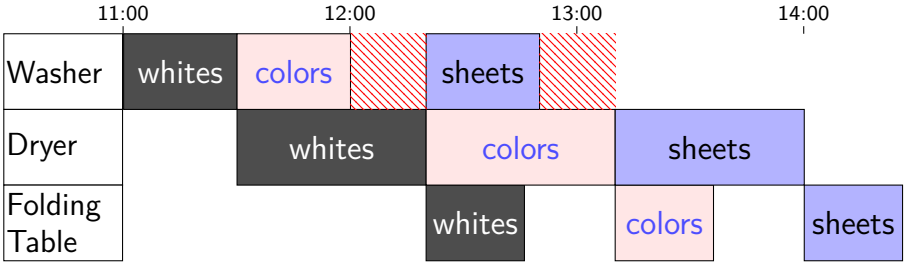
Waste (1)


11:00
12:00
13:00
14:00
Washer
whites
colors
sheets
Dryer
whites
colors
sheets
Folding Table
whites
colors
sheets

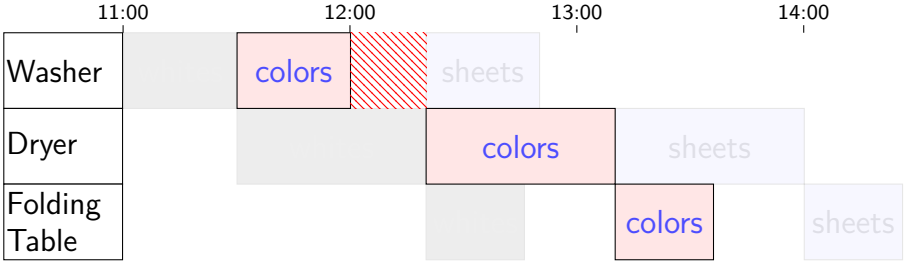
Waste (1)


wasted time!
11:00
12:00
13:00
14:00
Washer
Dryer
Folding Table
whites
colors
sheets
whites
colors
sheets
whites
colors
sheets

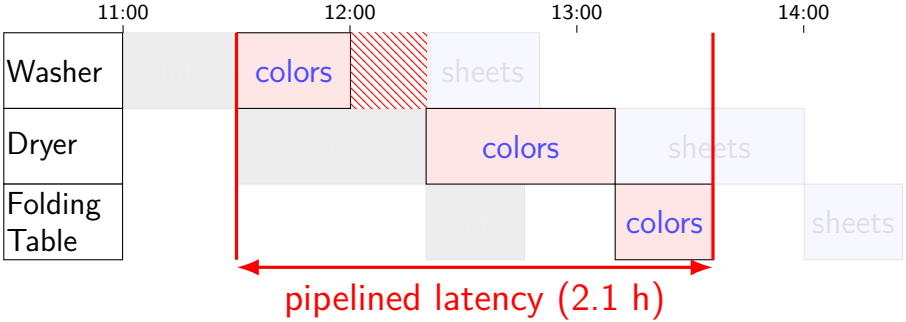
Waste (2)


11:00
12:00
13:00
14:00
Washer
Dryer
Folding Table
whites
colors
sheets
whites
colors
sheets
whites
colors
sheets

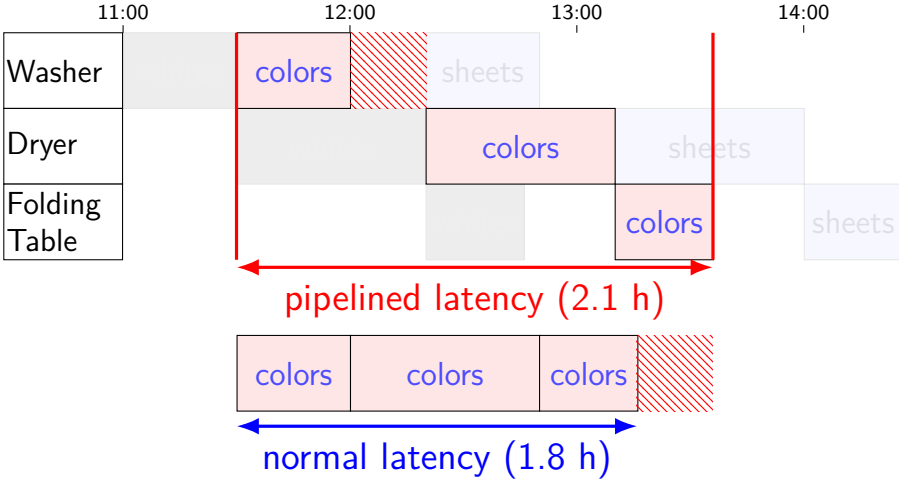
Latency — Time for One



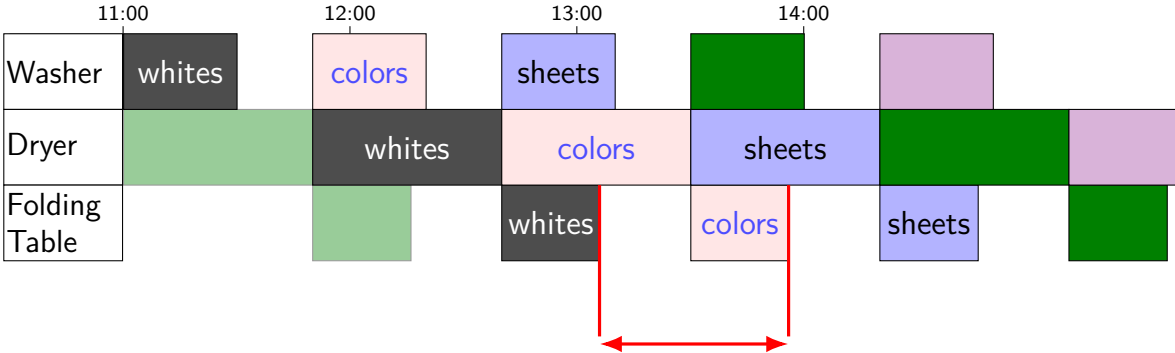
Latency — Time for One



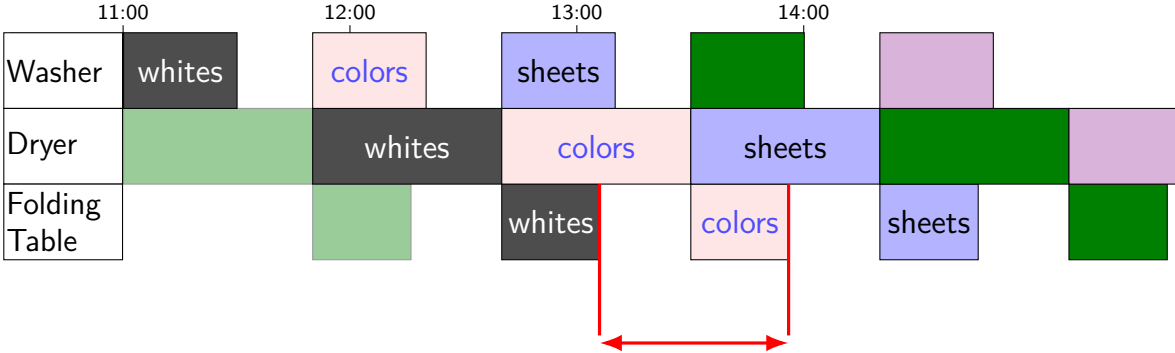
Latency — Time for One



Throughput — Rate of Many

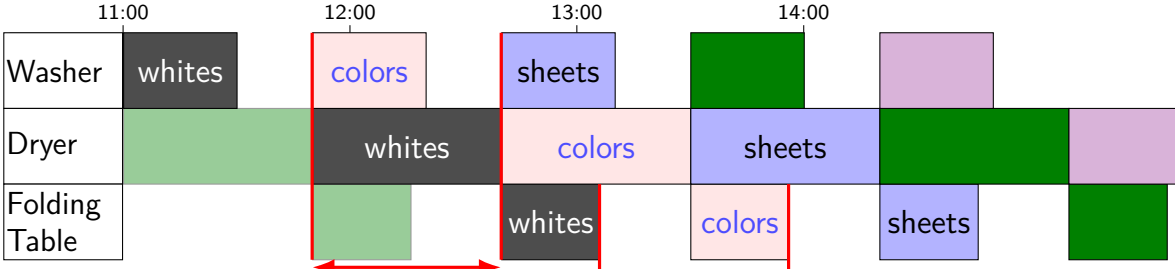


Throughput — Rate of Many



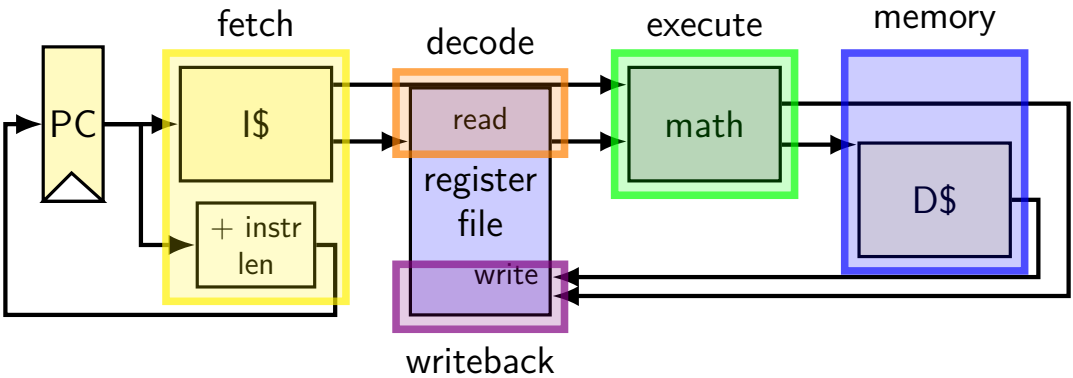
$$\frac{1 \text{ load}}{0.83\text{h}} = 1.2 \text{ loads/h}$$

Throughput — Rate of Many



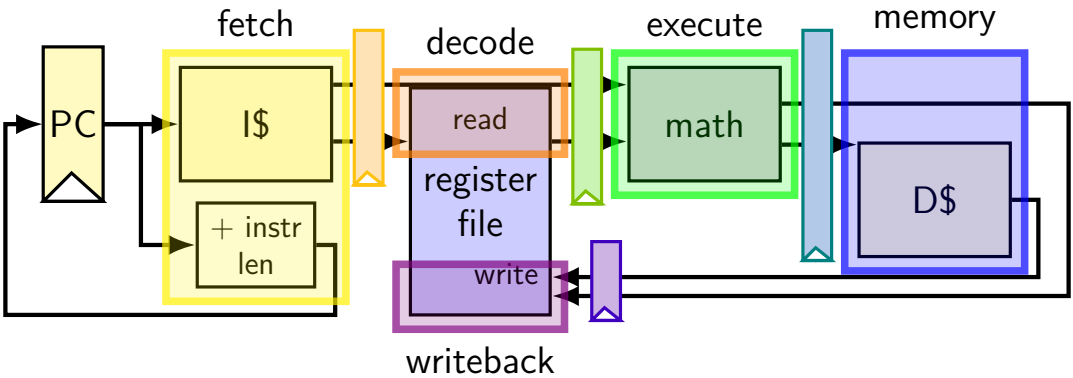
$$\frac{1 \text{ load}}{0.83\text{h}} = 1.2 \text{ loads/h}$$

adding stages (one way)



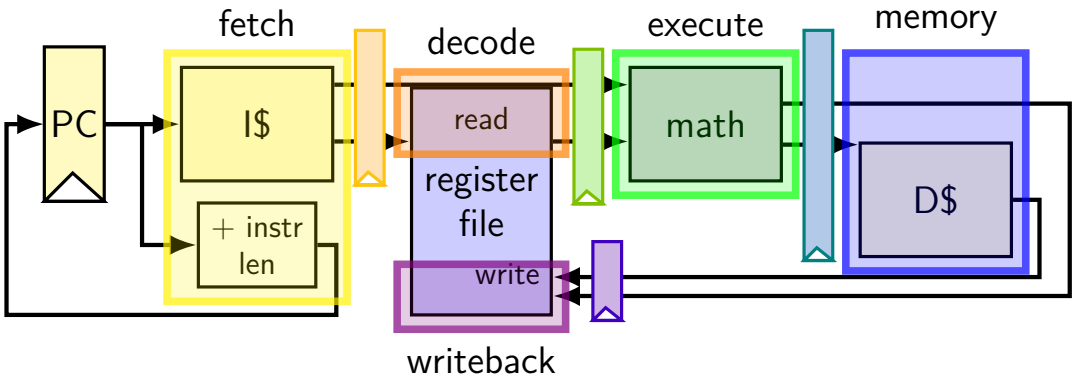
divide running instruction into steps
one way: fetch / decode / execute / memory / writeback

adding stages (one way)

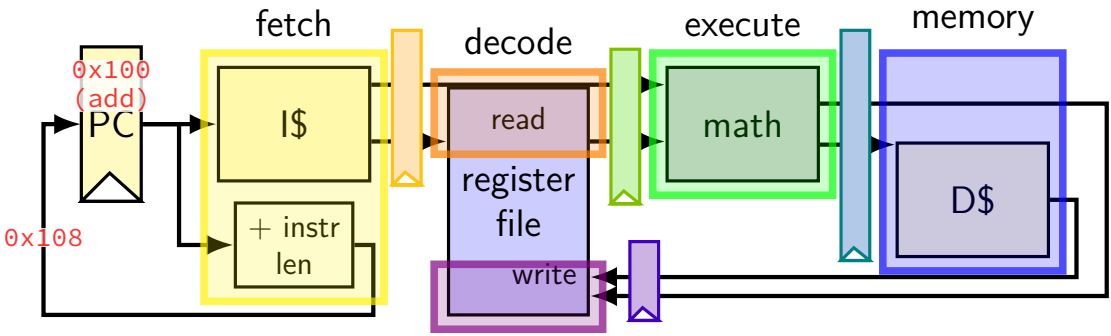


add ‘pipeline registers’ to hold values from instruction

running some instructions



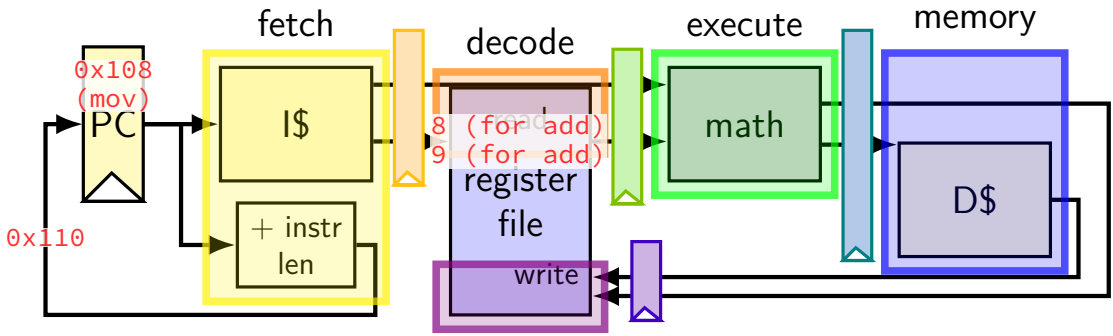
running some instructions




```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: xor %r12, %r13
```

cycle #	0	1	2	3	4	5	6	7	8
	F	D	E	M	W				
		F	D	E	M	W			
			F	D	E	M	W		

running some instructions




```
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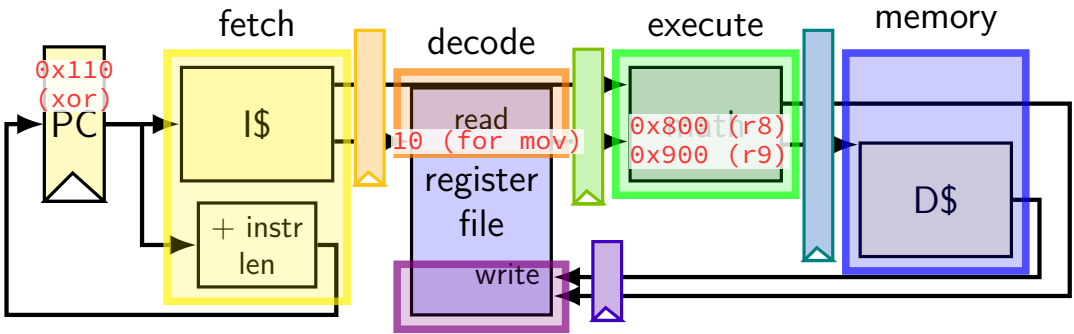
```

cycle #	0	1	2	3	4	5	6	7	8
	F	D	E	M	W				
		F	D	E	M	W			
			F	D	E	M	W		

running some instructions




```
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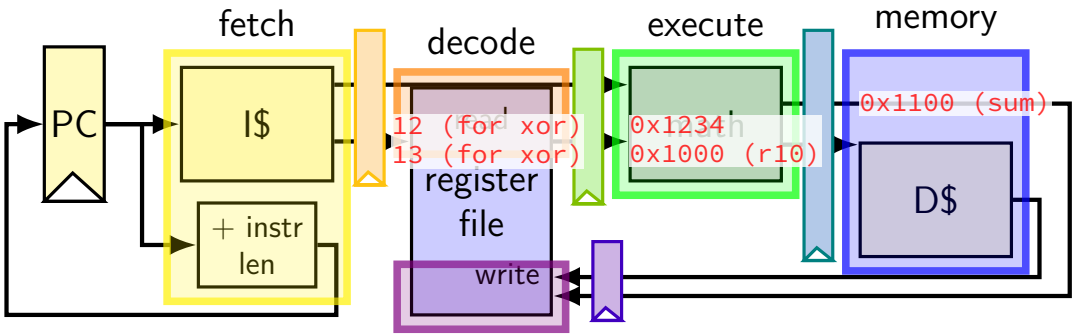
```

cycle #	0	1	2	3	4	5	6	7	8
	F	D	E	M	W				
		F	D	E	M	W			
			F	D	E	M	W		

running some instructions

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0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
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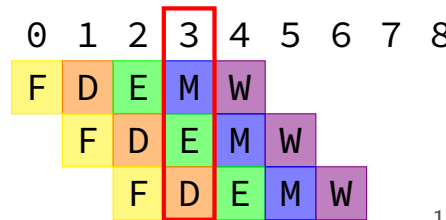
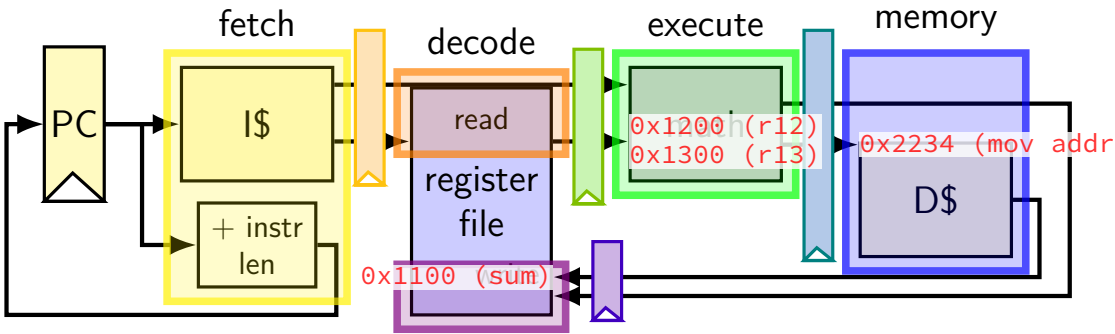
```



running some instructions




```
0x100: add %r8, %r9
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```

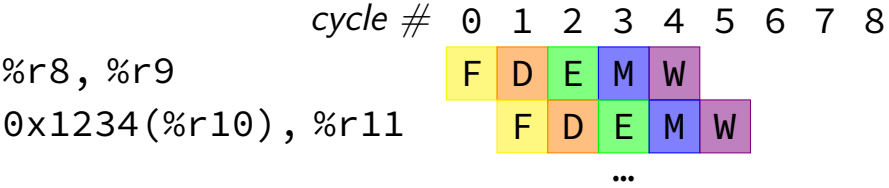
cycle #	0	1	2	3	4	5	6	7	8
	F	D	E	M	W				
		F	D	E	M	W			
			F	D	E	M	W		

why registers?

example: fetch/decode

need to store current instruction somewhere ...while fetching next one

exercise: throughput/latency (1)

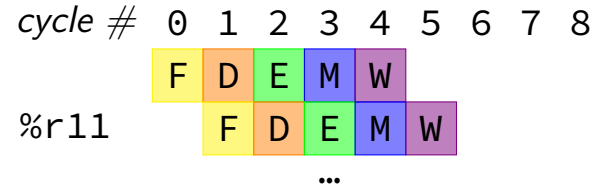


suppose cycle time is 500 ps

exercise: latency of one instruction?

A. 100 ps B. 500 ps C. 2000 ps D. 2500 ps E. something else

exercise: throughput/latency (1)




```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: …
```

suppose cycle time is 500 ps

exercise: latency of one instruction?

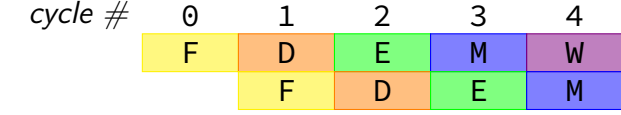
A. 100 ps B. 500 ps C. 2000 ps D. 2500 ps E. something else

exercise: throughput overall?

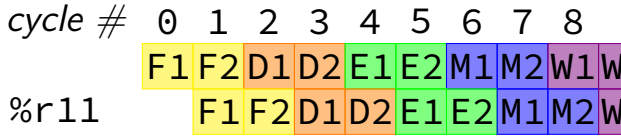
A. 1 instr/100 ps B. 1 instr/500 ps C. 1 instr/2000ps D. 1 instr/2500 ps
E. something else

exercise: throughput/latency (2)

```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: …
```



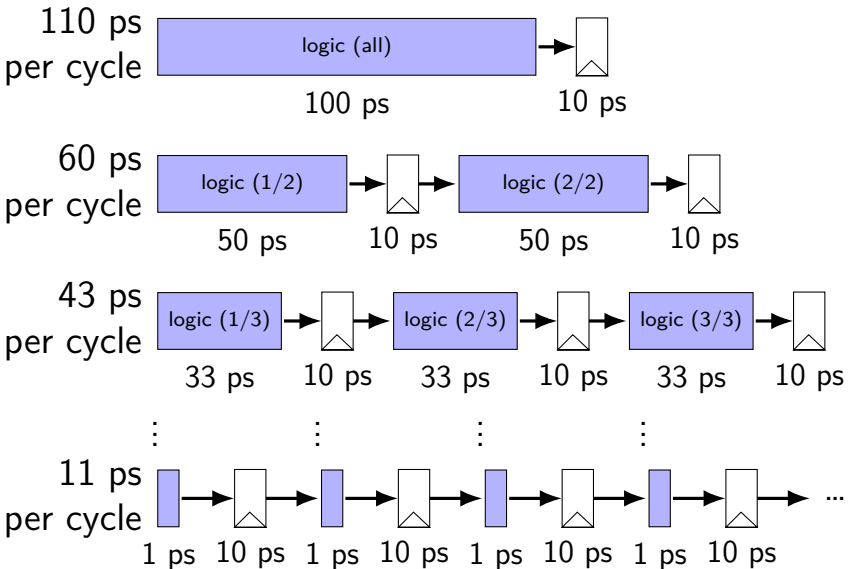

```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: …
```



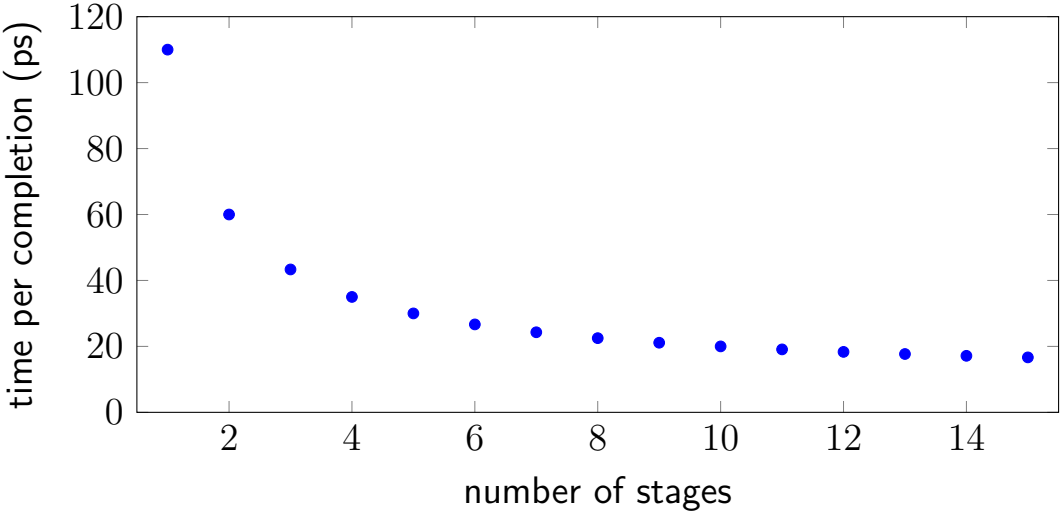
double number of pipeline stages (to 10) + decrease cycle time from 500 ps to 250 ps — throughput?

A. 1 instr/100 ps B. 1 instr/250 ps C. 1 instr/1000ps D. 1 instr/5000 ps
E. something else

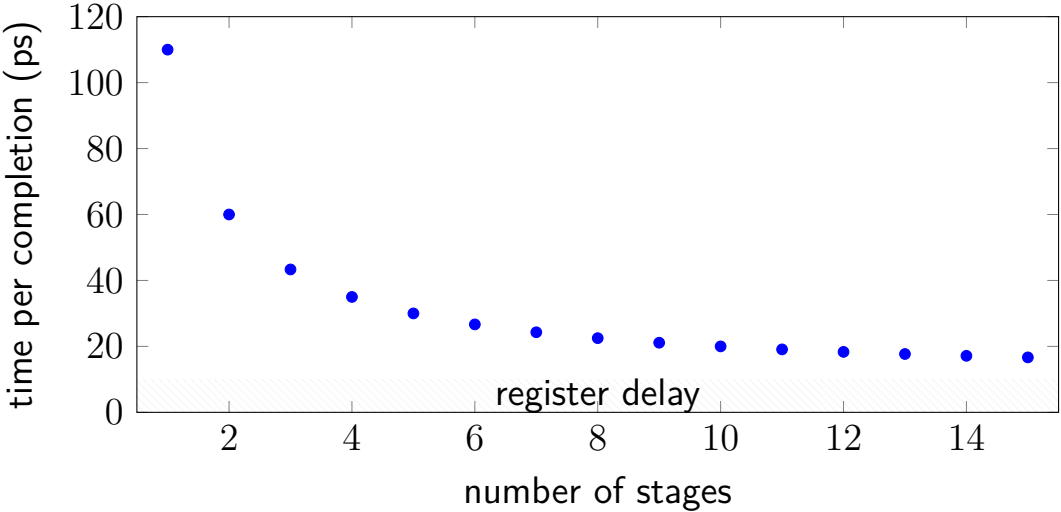
diminishing returns: register delays



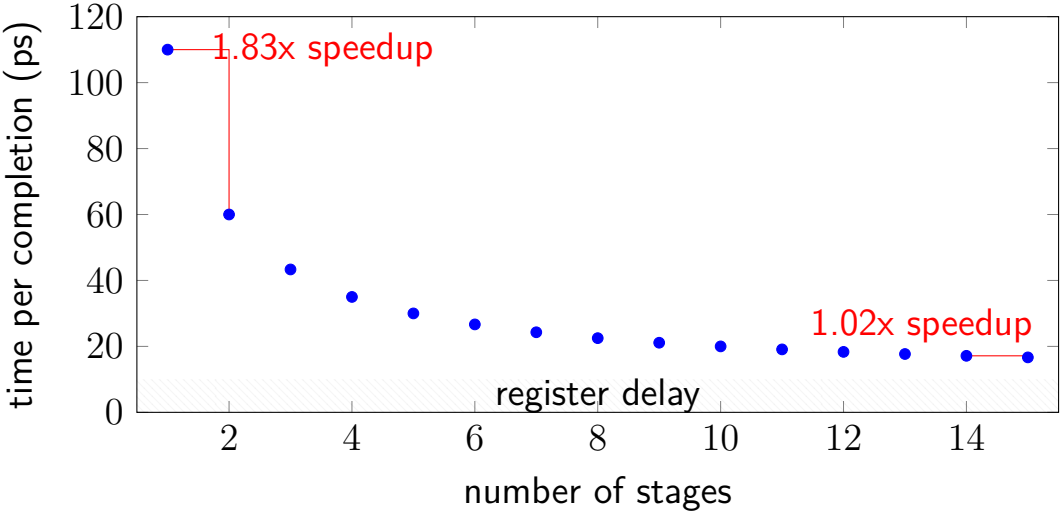
diminishing returns: register delays



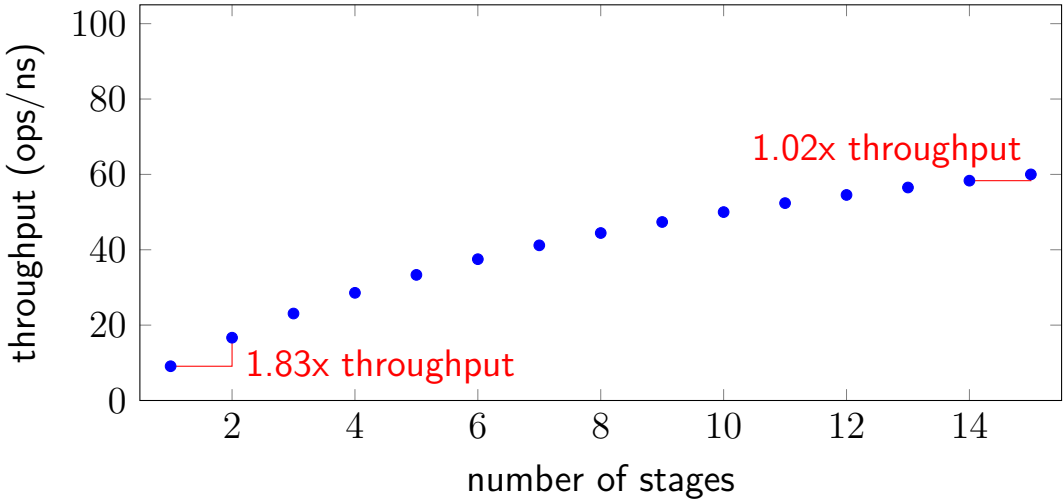
diminishing returns: register delays



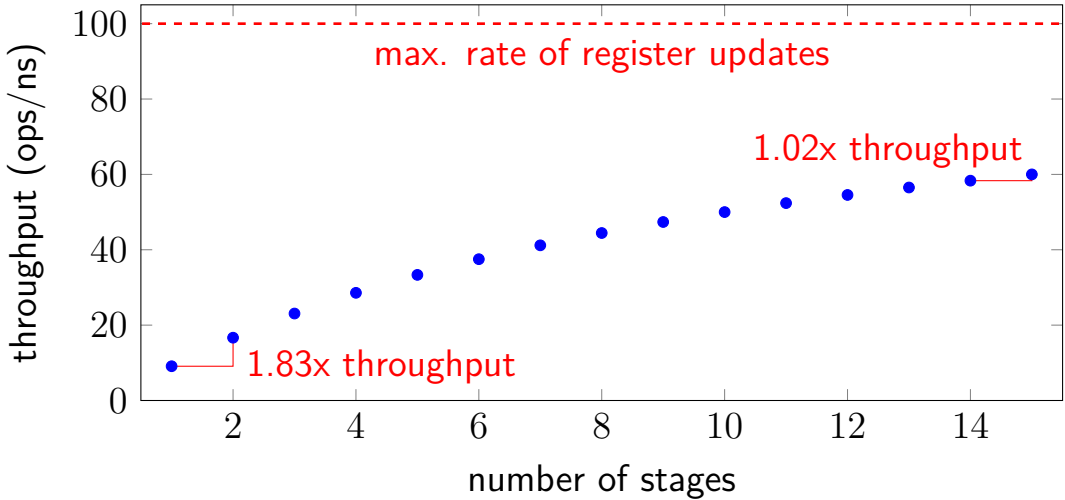
diminishing returns: register delays



diminishing returns: register delays



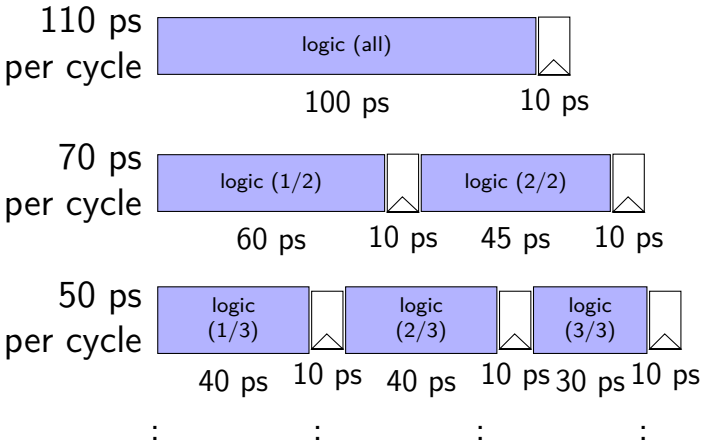
diminishing returns: register delays



diminishing returns: uneven split

Can we split up some logic (e.g. adder) arbitrarily?

Probably not...



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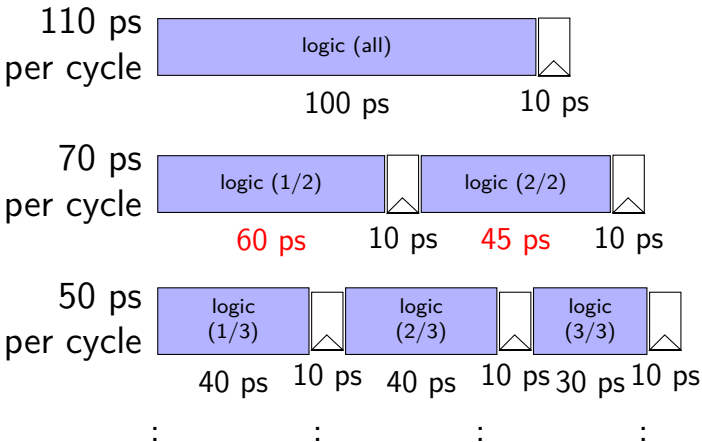

diminishing returns: uneven split

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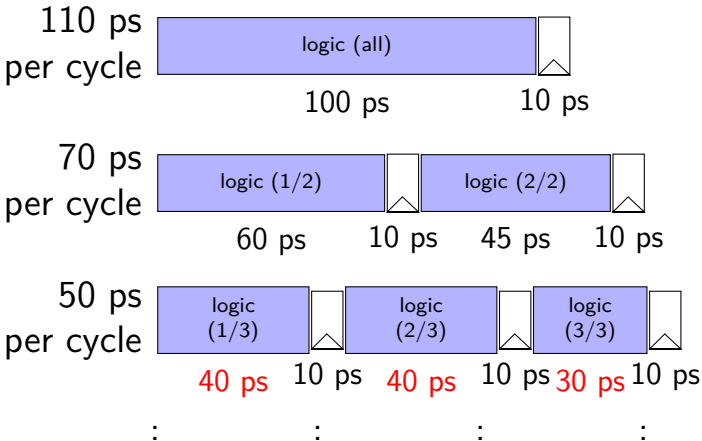
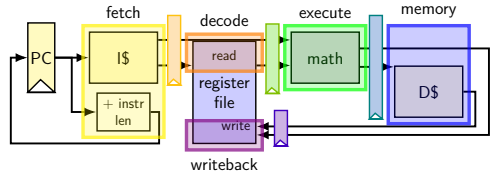


a data hazard

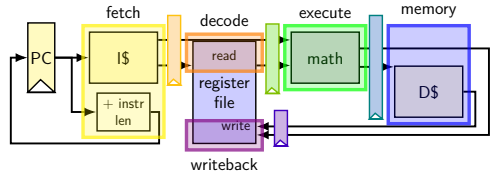
```
// initially %r8 = 800,
//           %r9 = 900, etc.
addq %r8, %r9    // R8 + R9 -> R9
addq %r9, %r8    // R9 + R8 -> R9
addq ...
addq ...
```



	fetch	fetch/decode		decode/execute			execute/memory		memory/writeback	
cycle	PC	rA	rB	R[rB]	R[rB]	rB	sum	rB	sum	rB
0	0x0									
1	0x2	8	9							
2		9	8	800	900	9				
3				900	800	8	1700	9		
4							1700	8	1700	9
5									1700	8

a data hazard

```
// initially %r8 = 800,
//           %r9 = 900, etc.
addq %r8, %r9    // R8 + R9 -> R9
addq %r9, %r8    // R9 + R8 -> R9
addq ...
addq ...
```



	fetch	fetch/decode		decode/execute			execute/memory		memory/writeback	
cycle	PC	rA	rB	R[rB]	R[rB]	rB	sum	rB	sum	rB
0	0x0									
1	0x2	8	9							
2		9	8	800	900	9				
3				900	800	8	1700	9		
4							1700	8	1700	9
5									1700	8

should be 1700

data hazard

```
addq %r8, %r9  // (1)
addq %r9, %r8  // (2)
```

step#	pipeline implementation	ISA specification
1	read r8, r9 for (1)	read r8, r9 for (1)
2	read r9, r8 for (2)	write r9 for (1)
3	write r9 for (1)	read r9, r8 for (2)
4	write r8 for (2)	write r8 ror (2)

pipeline reads older value...

instead of value ISA says was just written

data hazard compiler solution

```
addq %r8, %r9
nop
nop
addq %r9, %r8
```

one solution: change the ISA

all addqs take effect three instructions later
(assuming can read register value while it is being written back)

make it compiler's job

problem: recompile everytime processor changes?

data hazard compiler solution

```
addq %r8, %r9
nop
nop
addq %r9, %r8
```

one solution: change the ISA

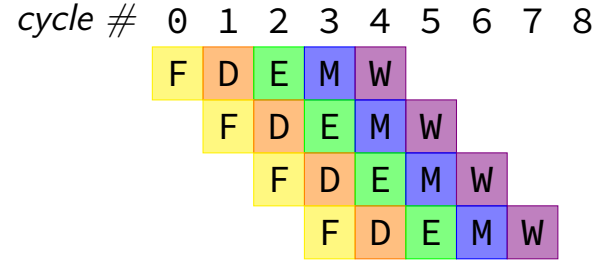
all addqs take effect three instructions later
(assuming can read register value while it is being written back)

make it compiler's job

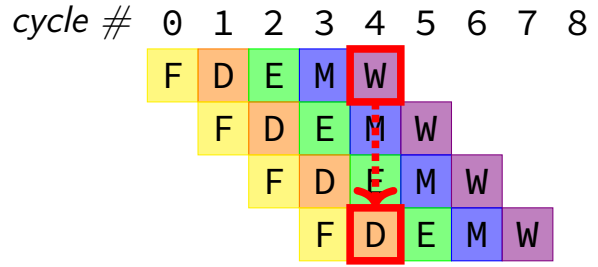
problem: recompile everytime processor changes?

stalling/nop pipeline diagram (1)

```
add %r8, %r9
nop
nop
addq %r9, %r8
```



stalling/nop pipeline diagram (1)

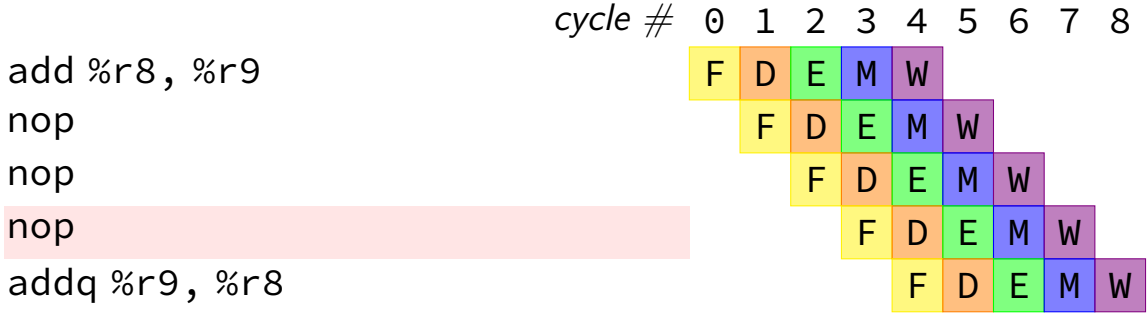



```
add %r8, %r9
nop
nop
addq %r9, %r8
```

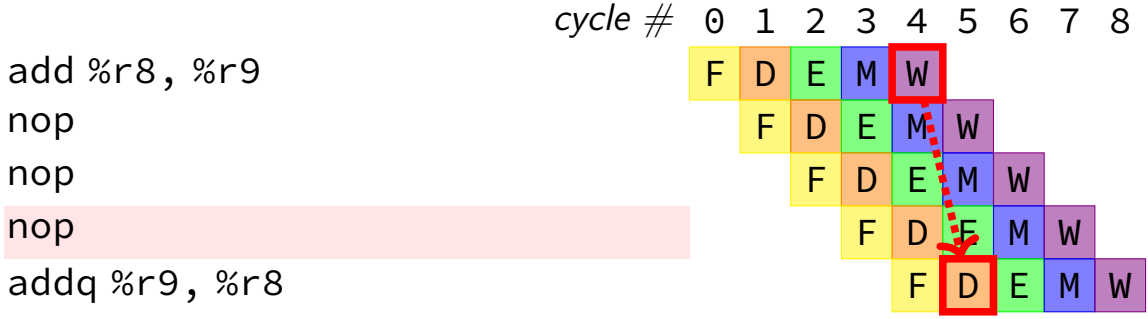
assumption:
if writing register value
register file will return that value for reads

not actually way register file worked in single-cycle CPU
(e.g. can read old %r9 while writing new %r9)

stalling/nop pipeline diagram (2)



stalling/nop pipeline diagram (2)



if we didn't modify the register file, we'd need an extra cycle

data hazard hardware solution

```
addq %r8, %r9
// hardware inserts: nop
// hardware inserts: nop
addq %r9, %r8
```

how about hardware add nops?

called stalling

extra logic:

- sometimes don't change PC
- sometimes put do-nothing values in pipeline registers

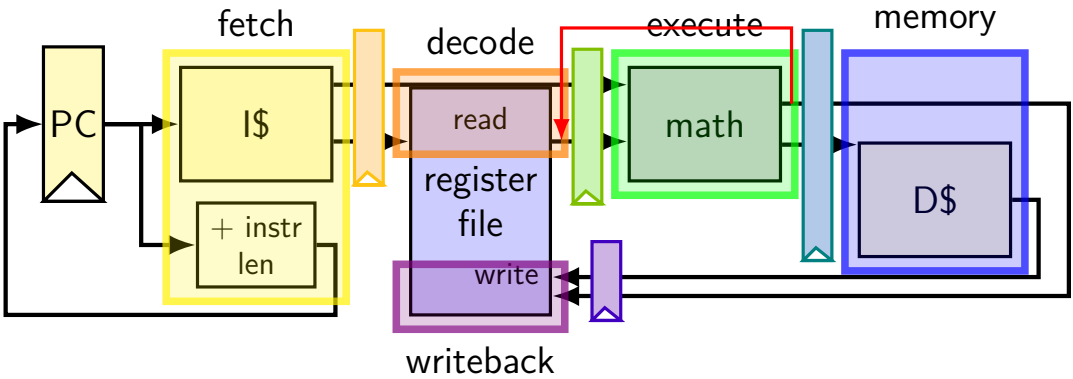
opportunity

```
// initially %r8 = 800,
//           %r9 = 900, etc.
0x0: addq %r8, %r9
0x2: addq %r9, %r8
...
```

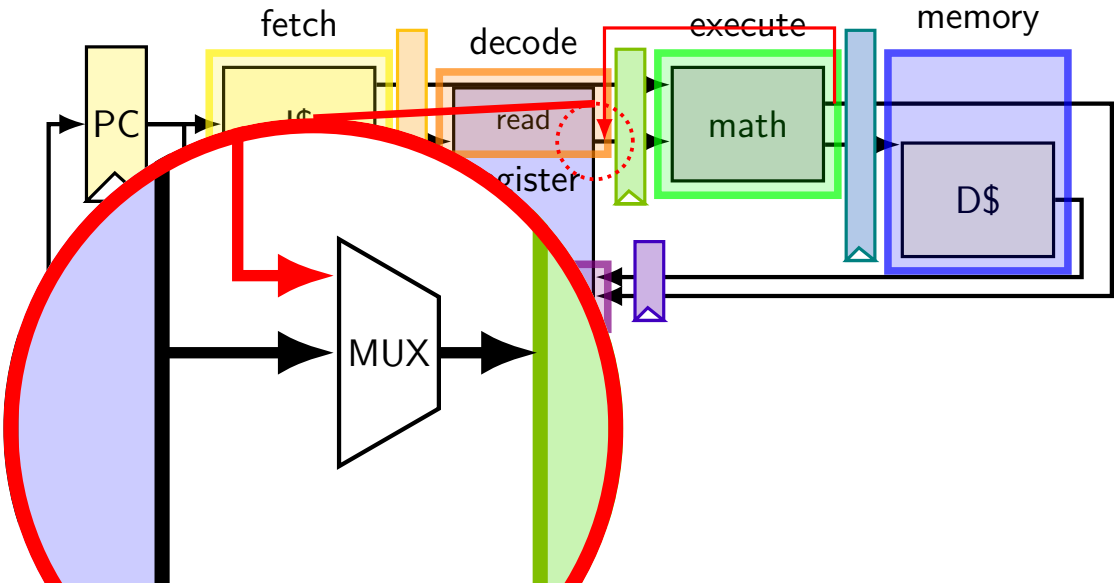
	fetch	fetch/decode		decode/execute			execute/memory		memory/writeback	
cycle	PC	rA	rB	R[rB	R[rB]	rB	sum	rB	sum	rB
0	0x0									
1	0x2	8	9							
2		9	8	800	900	9				
3				900	800	8	1700	9		
4							1700	8	1700	9
5									1700	8

should be 1700

exploiting the opportunity



exploiting the opportunity



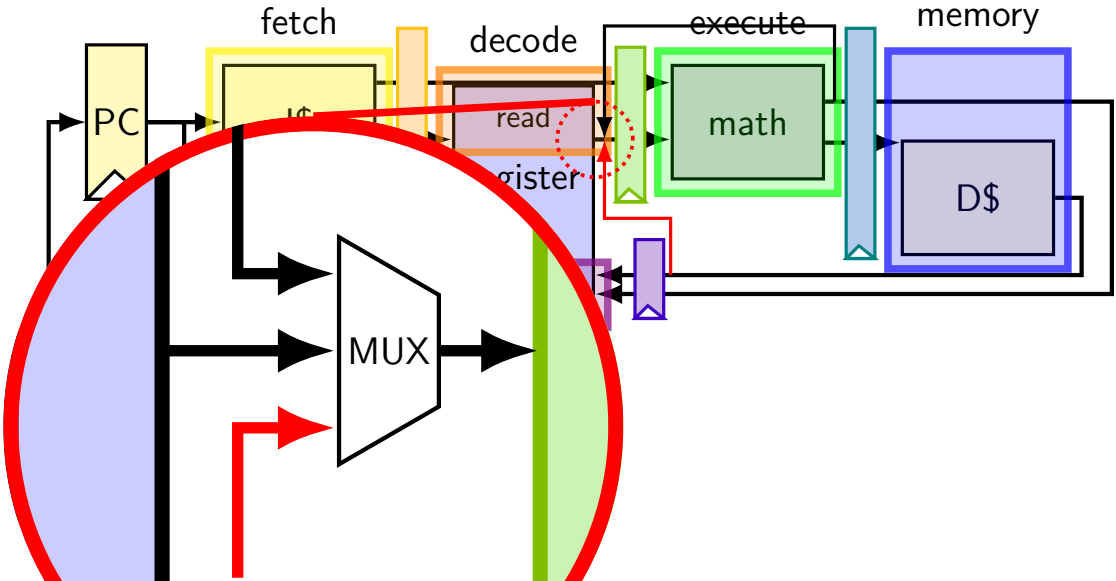
opportunity 2

```
// initially %r8 = 800,
//           %r9 = 900, etc.
0x0: addq %r8, %r9
0x2: nop
0x3: addq %r9, %r8
...
```

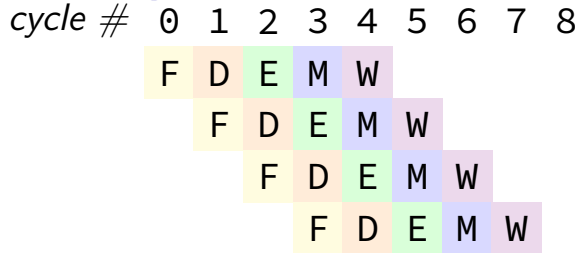
	fetch	fetch/decode		decode/execute			execute/memory		memory/writeback	
cycle	PC	rA	rB	R[rB	R[rB]	rB	sum	rB	sum	rB
0	0x0									
1	0x2	8	9							
2	0x3	---	---	800	900	9				
3		9	8	---	---	---	1700	9		
4				900	800	8	---	---	1700	9
5							1700	9	---	---
6									1700	9

should be 1700

exploiting the opportunity



exercise: forwarding paths



in subq, %r8 is _____ addq.

in xorq, %r9 is _____ addq.

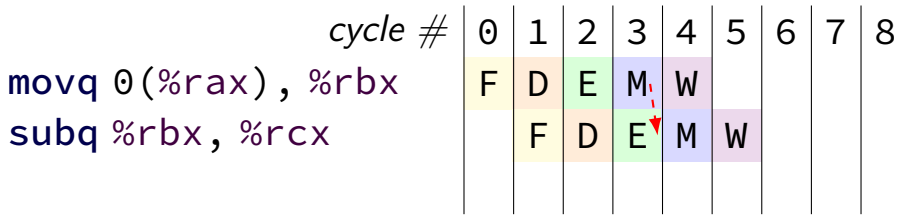
in andq, %r9 is _____ addq.

in andq, %r9 is _____ xorq.

A: not forwarded from

B-D: forwarded to decode from {execute,memory,writeback} stage of

unsolved problem

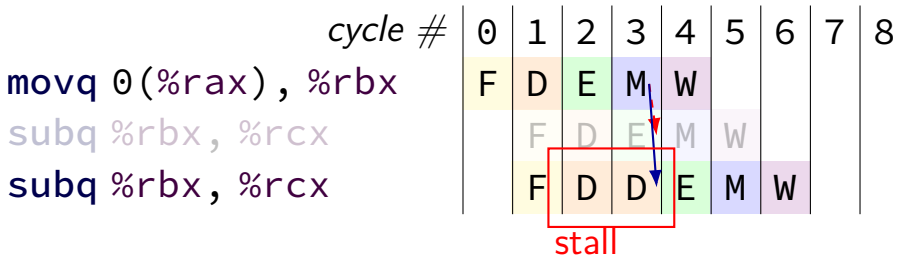


combine stalling and forwarding to resolve hazard

assumption in diagram: hazard detected in `subq`'s decode stage

(since easier than detecting it in fetch stage)

unsolved problem

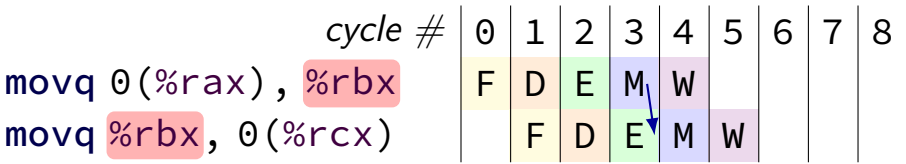


combine stalling and forwarding to resolve hazard

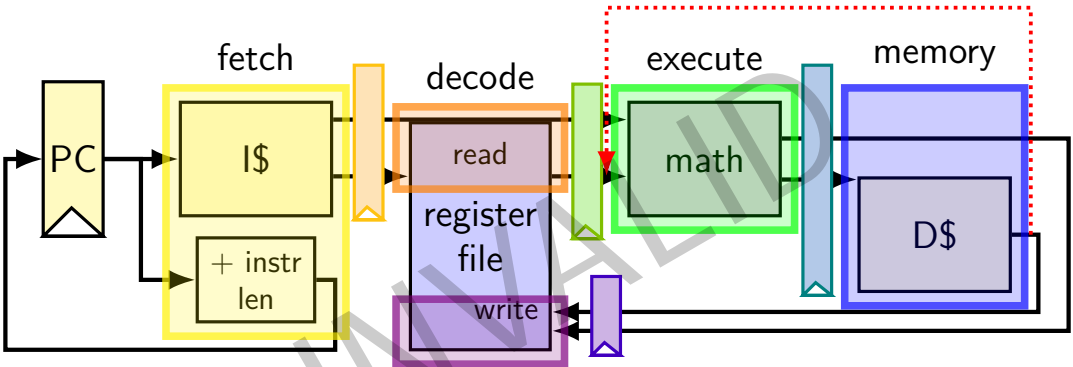
assumption in diagram: hazard detected in `subq`'s decode stage

(since easier than detecting it in fetch stage)

solveable problem

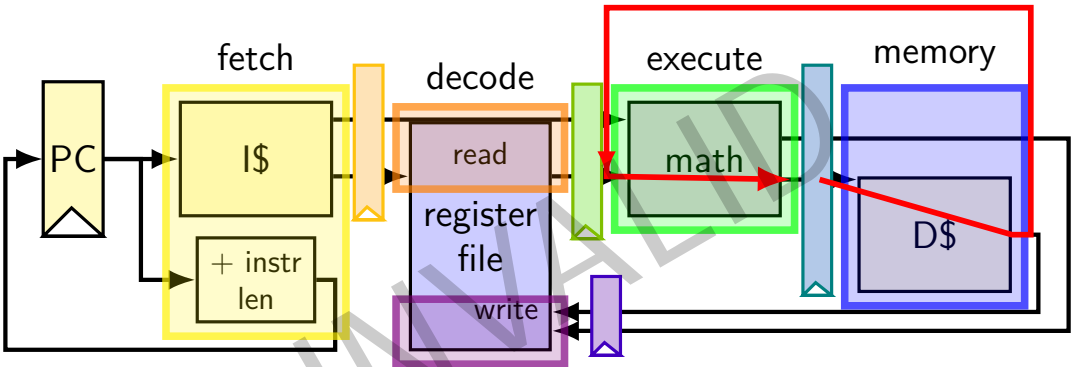


why can't we...



clock cycle needs to be long enough
to go through data cache AND
to go through math circuits!
(which we were trying to avoid by putting them in separate stages)

why can't we...



clock cycle needs to be long enough
to go through data cache AND
to go through math circuits!
(which we were trying to avoid by putting them in separate stages)

hazards versus dependencies

dependency — X needs result of instruction Y?

- has potential for being messed up by pipeline
- (since part of X may run before Y finishes)

hazard — will it not work in some pipeline?

- before extra work is done to "resolve" hazards
- multiple kinds: so far, *data hazards*

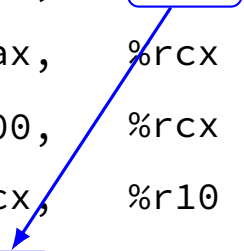
ex.: dependencies and hazards (1)

```
addq    %rax,   %rbx
subq    %rax,   %rcx
movq    $100,   %rcx
addq    %rcx,   %r10
addq    %rbx,   %r10
```

where are dependencies?
which are hazards in our pipeline?
which are resolved with forwarding?

ex.: dependencies and hazards (1)

```
addq    %rax, %rbx
subq    %rax, %rcx
movq    $100, %rcx
addq    %rcx, %r10
addq    %rbx, %r10
```



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```
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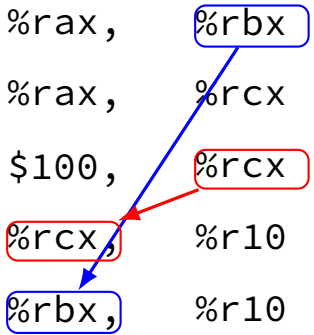
subq    %rax, %rcx
movq    $100, %rcx
addq    %rcx, %r10
addq    %rbx, %r10
```



where are dependencies?
which are hazards in our pipeline?
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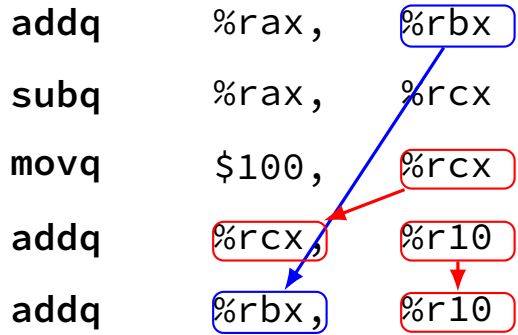
ex.: dependencies and hazards (1)



where are dependencies?
which are hazards in our pipeline?
which are resolved with forwarding?

pipeline with different hazards

example: 4-stage pipeline:
fetch/decode/execute+memory/writeback

```
                    // 4 stage   // 5 stage
addq %rax, %r8      //           // W
subq %rax, %r9      // W         // M
xorq %rax, %r10     // EM        // E
andq %r8,  %r11     // D         // D
```

pipeline with different hazards

example: 4-stage pipeline:
fetch/decode/execute+memory/writeback

```
                    // 4 stage   // 5 stage
addq %rax, %r8      //           // W
subq %rax, %r9      // W         // M
xorq %rax, %r10     // EM        // E
andq %r8,  %r11     // D         // D
```

addq/andq is hazard with 5-stage pipeline

addq/andq is **not** a hazard with 4-stage pipeline

pipeline with different hazards

example: 4-stage pipeline:
fetch/decode/execute+memory/writeback

```
                    // 4 stage   // 5 stage
addq %rax, %r8      //           // W
subq %rax, %r9      // W         // M
xorq %rax, %r10     // EM        // E
andq %r8,  %r11     // D         // D
```

more hazards with more pipeline stages

exercise: different pipeline

split execute into two stages: F/D/E1/E2/M/W

result only available near end of second execute stage

where does forwarding, stalls occur?

cycle #	0	1	2	3	4	5	6	7	8
(1) `addq %rcx, %r9`	F	D	E1	E2	M	W			
(2) `addq %r9, %rbx`									
(3) `addq %rax, %r9`									
(4) `movq %r9, (%rbx)`									
(5) `movq %rcx, %r9`									

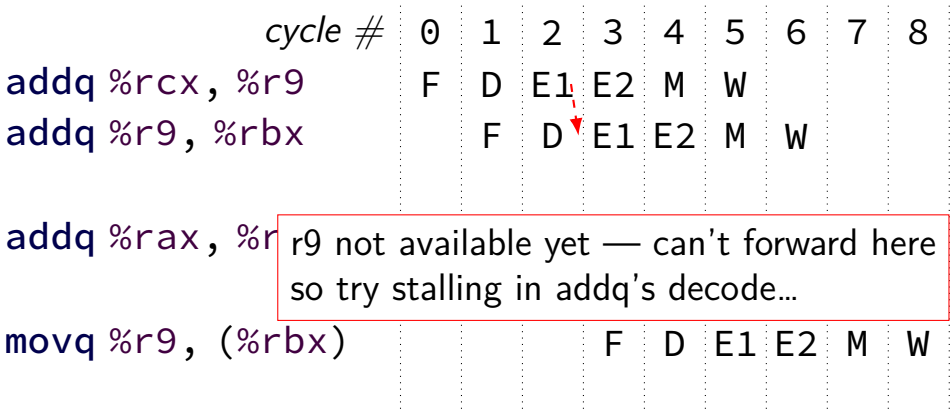
exercise: different pipeline

split execute into two stages: F/D/E1/E2/M/W

cycle #	0	1	2	3	4	5	6	7	8
`addq %rcx, %r9`	F	D	E1	E2	M	W			
`addq %r9, %rbx`									
`addq %rax, %r9`									
`movq %r9, (%rbx)`									

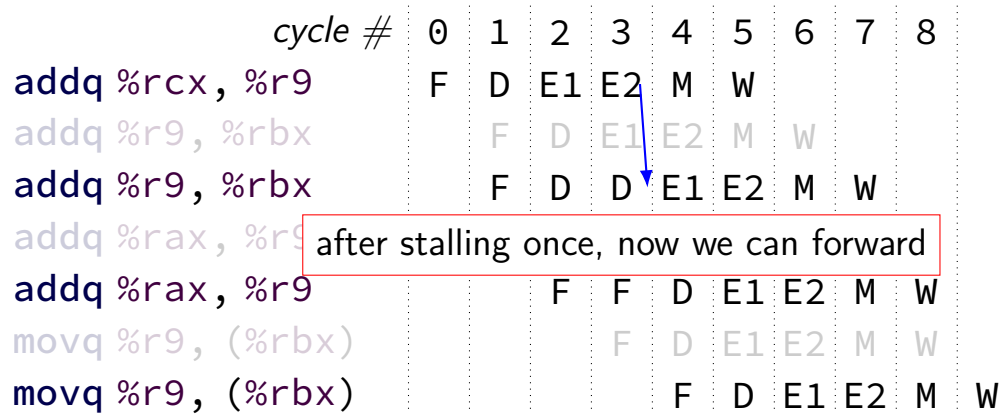
exercise: different pipeline

split execute into two stages: F/D/E1/E2/M/W



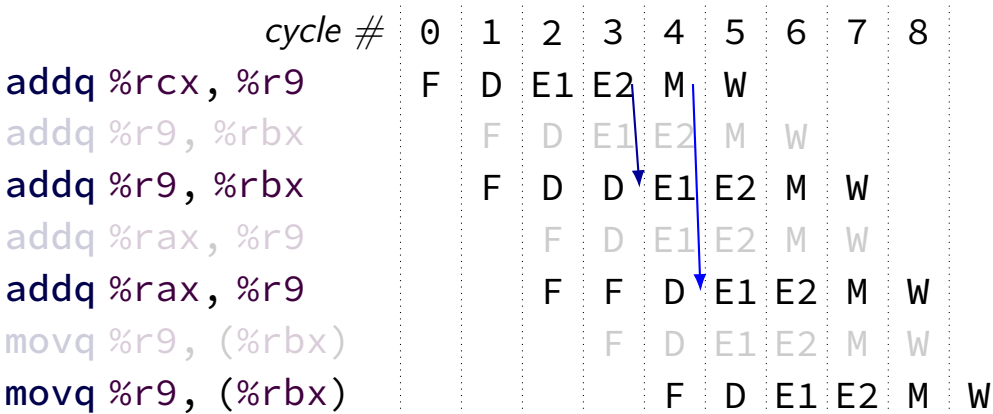
exercise: different pipeline

split execute into two stages: F/D/E1/E2/M/W



exercise: different pipeline

split execute into two stages: F/D/E1/E2/M/W



exercise: different pipeline

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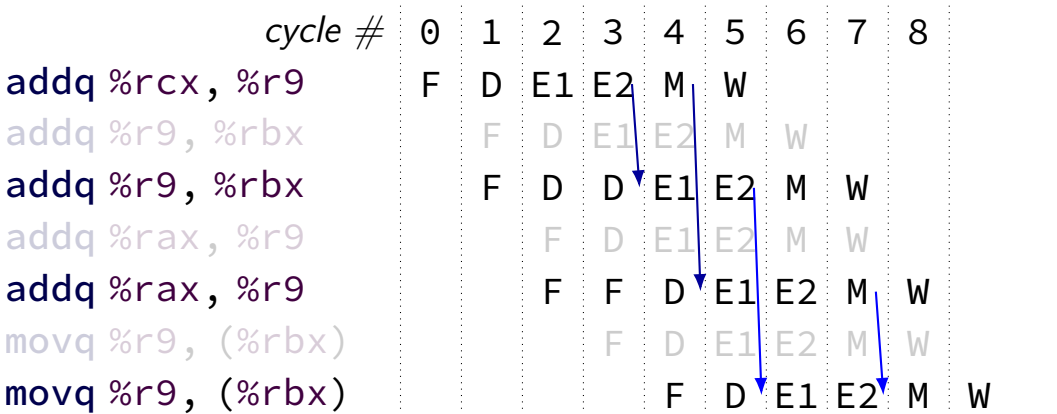


control hazard

```
0x00: cmpq %r8, %r9
0x08: je   0xFFFF
0x10: addq %r10, %r11
```

	fetch	fetch→decode	decode→execute		execute→writeback			...
cycle	PC	rA	rB	R[rA]	R[rB]	result	...	...	...
0	0x0								
1	0x8	8	9						
2	???	---	---	800	900				
3	???	---	---	---	---	less than			

control hazard

```
0x00: cmpq %r8, %r9
0x08: je   0xFFFF
0x10: addq %r10, %r11
```

	fetch	fetch→decode	decode→execute		execute→writeback			...
cycle	PC	rA	rB	R[rA]	R[rB]	result	...	...	...
0	0x0								
1	0x8	8	9						
2	???	---	---	800	900				
3	???	---	---	---	---	less than			

0xFFFF if R[8] = R[9]; 0x10 otherwise

jXX: stalling?

```
cmpq %r8, %r9
jne LABEL        // not taken
xorq %r10, %r11
movq %r11, 0(%r12)
...
```

cmpq %r8, %r9

jne LABEL

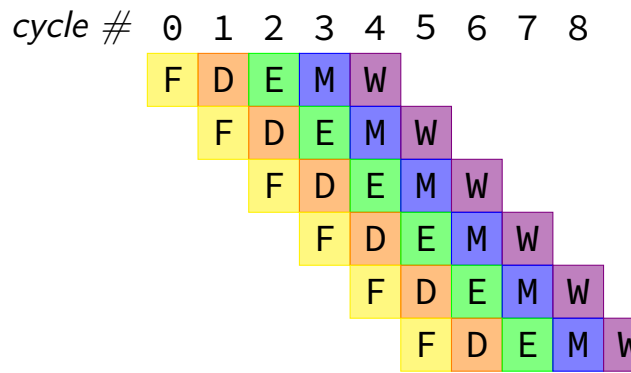
(do nothing)

(do nothing)

xorq %r10, %r11

movq %r11, 0(%r12)

…



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cmpq %r8, %r9

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(do nothing)

(do nothing)

xorq %r10, %r11

movq %r11, 0(%r12)

…

jXX: stalling?

```
cmpq %r8, %r9
jne LABEL        // not taken
xorq %r10, %r11
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...
```

cmpq %r8, %r9

jne LABEL

(do nothing)

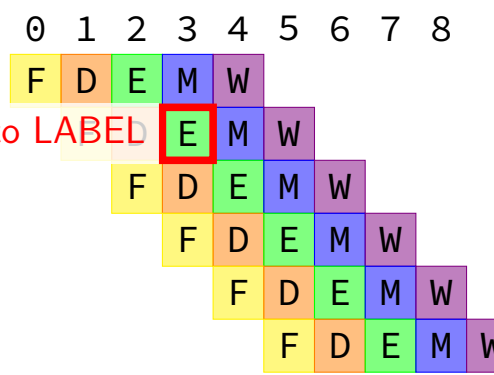
(do nothing)

xorq %r10, %r11

movq %r11, 0(%r12)

…

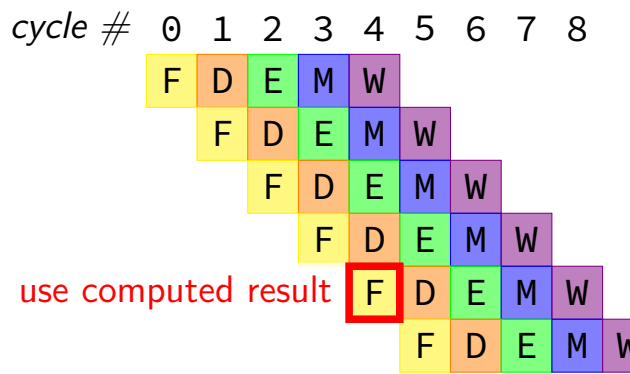
compute if jump goes to LABEL



jXX: stalling?

```
cmpq %r8, %r9
jne LABEL        // not taken
xorq %r10, %r11
movq %r11, 0(%r12)
...
```

```
cmpq %r8, %r9
jne LABEL
(do nothing)
(do nothing)
xorq %r10, %r11
movq %r11, 0(%r12)
…
```



making guesses

```
        cmpq %r8, %r9
        jne LABEL
        xorq %r10, %r11
        movq %r11, 0(%r12)
        ...

LABEL:  addq %r8, %r9
        imul %r13, %r14
        ...
```

speculate (guess): jne won't go to LABEL

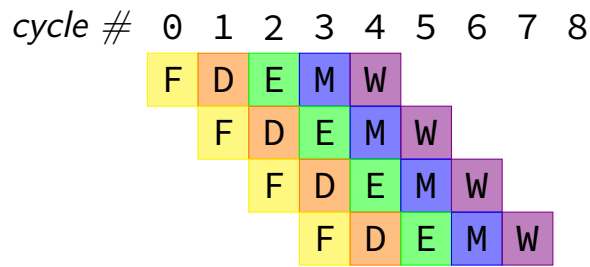
right: 2 cycles faster!; wrong: undo guess before too late

jXX: speculating right (1)

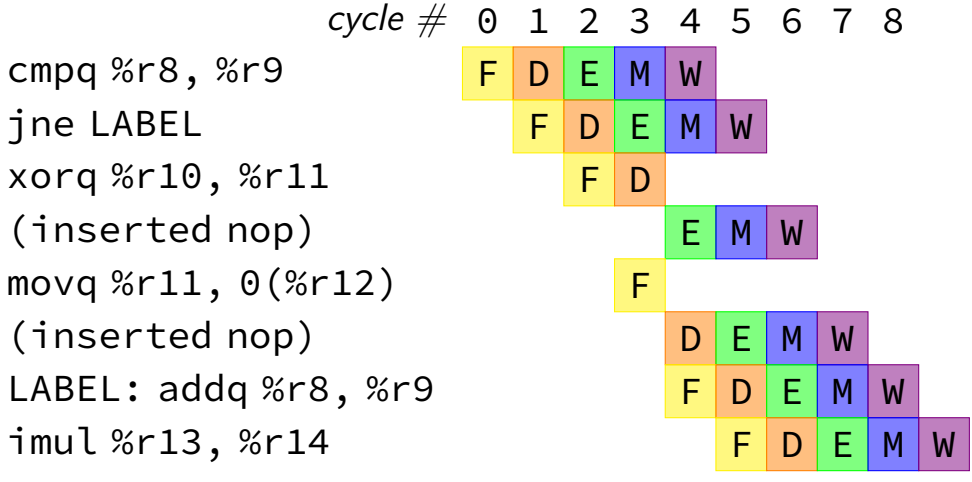
```
        cmpq %r8, %r9
        jne LABEL
        xorq %r10, %r11
        movq %r11, 0(%r12)
        ...

LABEL:  addq %r8, %r9
        imul %r13, %r14
        ...
```

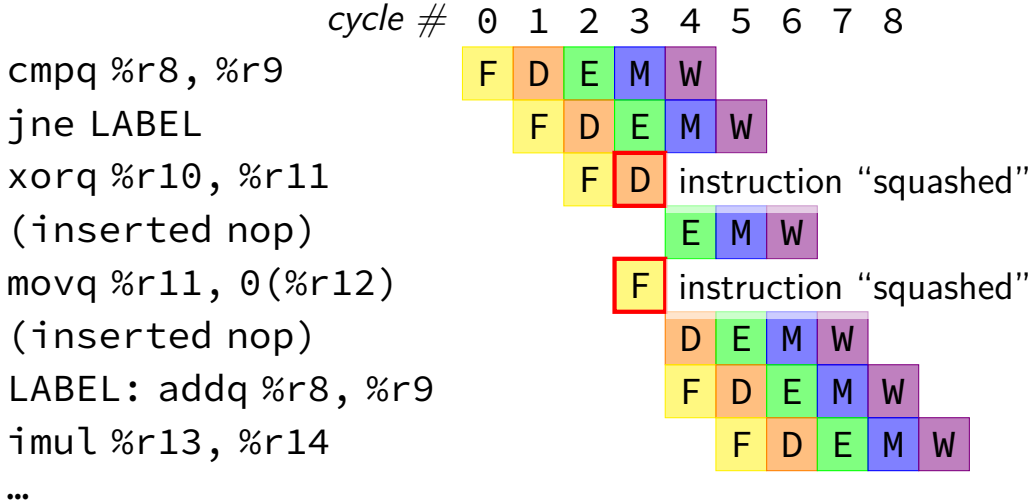
```
cmpq %r8, %r9
jne LABEL
xorq %r10, %r11
movq %r11, 0(%r12)
…
```



jXX: speculating wrong



jXX: speculating wrong



“squashed” instructions

on misprediction need to undo partially executed instructions

mostly: remove from pipeline registers

more complicated pipelines: replace written values in cache/registers/etc.

performance

hypothetical instruction mix

kind	portion	cycles (predict not-taken)	cycles (stall)
taken jXX	3%	3	3
non-taken jXX	5%	1	3
others	92%	1*	1*

* — ignoring data hazards

performance

hypothetical instruction mix

kind	portion	cycles (predict not-taken)	cycles (stall)
taken jXX	3%	3	3
non-taken jXX	5%	1	3
others	92%	1*	1*

predict: $3 \times .03 + 1 \times .05 + 1 \times .92 =$ 1.06 cycles/instr.

stall: $3 \times .03 + 3 \times .05 + 1 \times .92 =$ 1.16 cylces/instr. ($1.19 \div 1.09 \approx 1.09$x faster)

* — ignoring data hazards

backup slides

exercise: forwarding paths (2)

cycle # 0 1 2 3 4 5 6 7 8

```
addq %r8, %r9
subq %r8, %r9
ret (goes to andq)
andq %r10, %r9
```

in subq, %r8 is _____ addq.

in subq, %r9 is _____ addq.

in andq, %r9 is _____ subq.

in andq, %r9 is _____ addq.

A: not forwarded from

B-D: forwarded to decode from {execute,memory,writeback} stage of