last time

public/private key pairs

- give public key to (potentially) everyone
- keep private key secret (even from correspondents)
- asymmetric encryption using public key
- digital signature using private key

replay attacks

- encrypted/signed/MAC'd/etc. messages can be used out-of-context
- fix: include needed context/prevent reuse

anonymous feedback

'pipeline HW link didn't work — when will it'

should be corrected now, but marked tentative since we haven't covered lecture material yet

labeled due just before Thanksgiving break right now

- will adjust if needed

TAing next semester?

Yes, I am definitely looking for TAs!

won't make final hiring decisions about current students until after final exam

most likely won't reach TA hour cap

getting public keys?

browser talking to websites
needs public keys of every single website?

not really feasible, but...

certificate idea

let's say A has B's public key already.

if C wants B's public key and knows A's already:

A can generate "certificate" for B:

- "B's public key is XXX" AND
- Sign(A's private key, "B's public key is XXX")

B send copy of their "certificate" to C (most common idea)

if C trusts A, now C has B's public key

- if C does not trust A, well, can't trust this either

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certificate authorities

websites (and others) go to *certificates authorities* with their public key

certificate authorities sign messages like:
"The public key for foo.com is XXX."

signed message called *certificate*

send certificates to browsers to verify identity

example web certificate (1)

```
    Version: 3 (0x2)
    Serial Number: 7b:df:f6:ae:2e:d7:db:74:d3:c5:77:ac:bc:44:bf:1b
    Signature Algorithm: sha256WithRSAEncryption
    Issuer:
        countryName               = US
        stateOrProvinceName       = MI
        localityName              = Ann Arbor
        organizationName          = Internet2
        organizationalUnitName    = InCommon
        commonName                = InCommon RSA Server CA
    Validity
        Not Before: Apr 25 00:00:00 2023 GMT
        Not After : Apr 24 23:59:59 2024 GMT
    Subject:
        countryName               = US
        stateOrProvinceName       = Virginia
        organizationName          = University of Virginia
        commonName                = canvas.its.virginia.edu
....
    X509v3 extensions:
....
        X509v3 Subject Alternative Name: DNS:canvas.its.virginia.edu
```

example web certificate (2)

```
....
    Subject Public Key Info:
        Public Key Algorithm: rsaEncryption
            RSA Public-Key: (2048 bit)
            Modulus:
                00:a2:fb:5a:fb:2d:d2:a7:75:7e:eb:f4:e4:d4:6c:
                94:be:91:a8:6a:21:43:b2:d5:9a:48:b0:64:d9:f7:
                f1:88:fa:50:cf:d0:f3:3d:8b:cc:95:f6:46:4b:42:

....
Signature Algorithm: sha256WithRSAEncryption
Signature Value:
    24:3a:67:c8:0d:ef:eb:8c:eb:ba:8f:d5:11:d2:1e:ea:44:eb:
    fe:af:93:7d:d9:4a:2b:44:a3:7f:47:50:aa:d1:b3:9c:a8:a8:
....
```

certificate chains

That certificate signed by “InCommon RSA Server CA”

CA = certificate authority

so their public key, comes with my OS/browser?

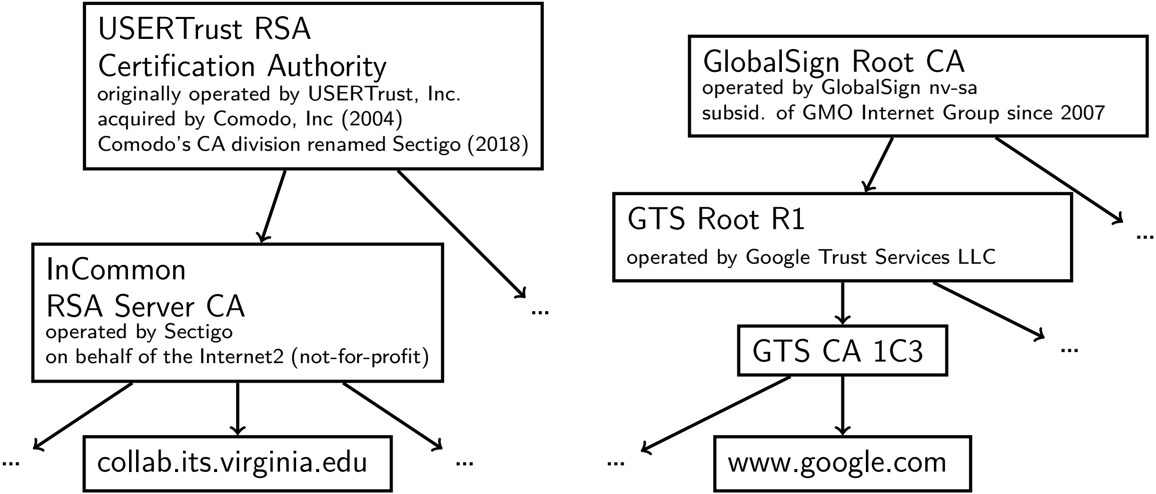
not exactly...

they have their own certificate signed by “USERTrust RSA Certification Authority”

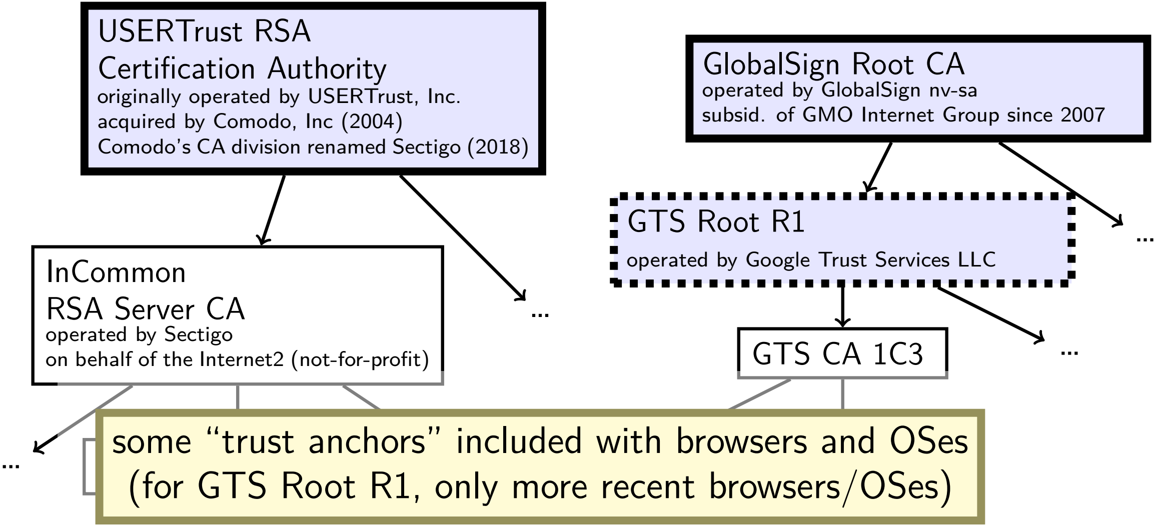
and their public key comes with your OS/browser?

(but both CAs now operated by UK-based Sectigo)

certificate hierarchy



certificate hierarchy



how many trust anchors?

Mozilla Firefox (as of 27 Feb 2023)

155 trust anchors
operated by 55 distinct entities

Microsoft Windows (as of 27 Feb 2023)

237 trust anchors
operated by 86 distinct entities

public-key infrastructure

ecosystem with certificate authorities
and certificates for everyone

called “public-key infrastructure”

several of these:

- for verifying identity of websites
- for verifying origin of domain name records (kind-of)
- for verifying origin of applications in some OSes/app stores/etc.
- for encrypted email in some organizations
- …

exercise

exercise: how should website certificates verify identity?

how do certificate authorities verify

for web sites, set by CA/Browser Forum

organization of:

- everyone who ships code with list of valid certificate authorities
  - Apple, Google, Microsoft, Mozilla, Opera, Cisco, Qihoo 360, Brave, …
- certificate authorities

decide on rules (“baseline requirements”) for what CAs do

BR domain name identity validation

options involve CA choosing random value and:

sending it to domain contact (with domain registrar) and receive response with it, or

observing it placed in DNS or website or sent from server in other specific way

exercise: problems this doesn't deal with?

some other things public CAs do

keep their private keys in tamper-resistant hardware

maintain publicly-accessible database of *revoked* certificates

- some browsers check these, sometimes

certificate transparency

- public logs of every certificate issued
- some browsers reject non-logged certificates
- so you can tell if bad certificate exists for your website

'CAA' records in the domain name system

- can indicate which CAs are allowed to issue certificates in DNS
- (but CAs apparently not required to use DNSSEC (certificate infrastructure for signing domain name records) when looking this up)

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motivation: summary for signature

digital signatures typically have size limit

...but we want to sign very large messages

solution: get secure "summary" of message

cryptographic hash

hash(M) = X

given X:

hard to find message other than by guessing

given X, M:

hard to find second message so that hash(second message) = H

example uses:

substitute for original message in digital signature

building message authentication codes

password hashing

cryptographic hash functions need (basically) guessing to 'reverse'

idea: store cryptographic hash of password instead of password

- attacker who gets hash doesn't get password
- but can still check entered password is correct

password hashing

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problem: with fast hash function, can try lots of guesses fast

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idea: store cryptographic hash of password instead of password

- attacker who gets hash doesn't get password
- but can still check entered password is correct

problem: with fast hash function, can try lots of guesses fast

fix: special slow/resource-intensive cryptograph hash functions

- Argon2i
- scrypt
- PBKDF2

random numbers

want keys, etc. to be unguessable and evenly distributed

solution: random numbers

but: many random number functions are not cryptographically secure!

- example NOT SECURE: ~~C `rand()`; Python's `random.random`~~
- better: Python's `secrets`, `os.urandom`; Linux `getrandom()`, `/dev/urandom`

extra effort to ensure not guessable

need to incorporate "entropy" from unpredictable sources

- deliberately unstable circuit; exact timing of input/output; etc.

just asymmetric?

given public-key encryption + digital signatures...

why bother with the symmetric stuff?

symmetric stuff much faster

symmetric stuff much better at supporting larger messages

key agreement

problem: A has B's public encryption key
wants to choose shared secret

some ideas:

- A chooses a key, sends it encrypted to B
- A sends a public key encrypted B, B chooses a key and sends it back

key agreement

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some ideas:

- A chooses a key, sends it encrypted to B
- A sends a public key encrypted B, B chooses a key and sends it back

alternate model:

- both sides generate random values
- derive public-key like "key shares" from values
- use math to combine "key shares"
- kinda like A + B both sending each other public encryption keys

Diffie-Hellman key agreement (2)

A and B want to agree on shared secret

A chooses random value Y

A sends public value derived from Y (“key share”)

B chooses random value Z

B sends public value derived from Z (“key share”)

A combines Y with public value from B to get number

B combines Z with public value from A to get number

and b/c of math chosen, both get same number

Diffie-Hellman key agreement (1)

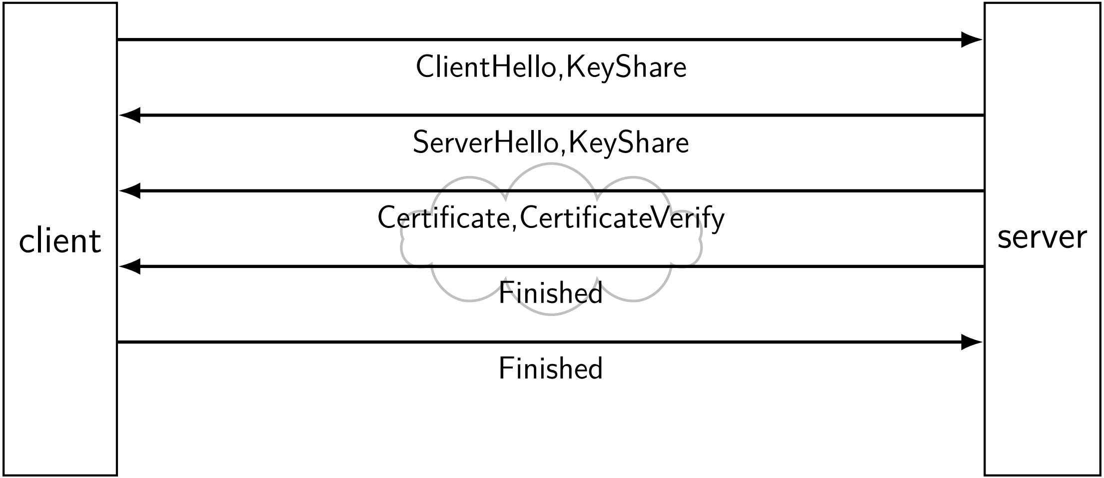
math requirement:

some f, so $f(f(X,Y),Z) = f(f(X,Z),Y)$
(that's hard to invert, etc.)

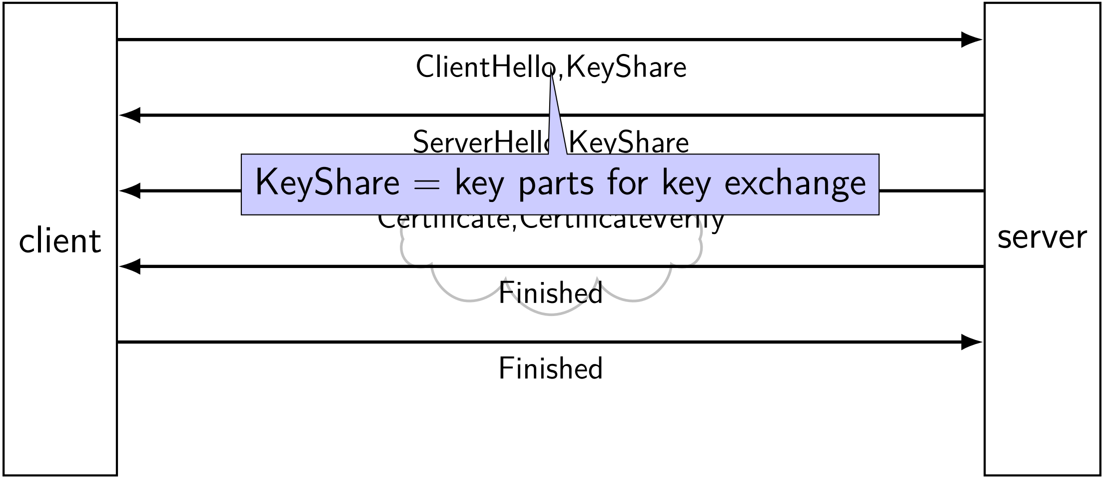
choose X in advance and:

A randomly chooses Y	B randomly chooses Z
A sends $f(X,Y)$ to B	B sends $f(X,Z)$ to A
A computes $f(f(X,Z),Y)$	B computes $f(f(X,Y),Z)$

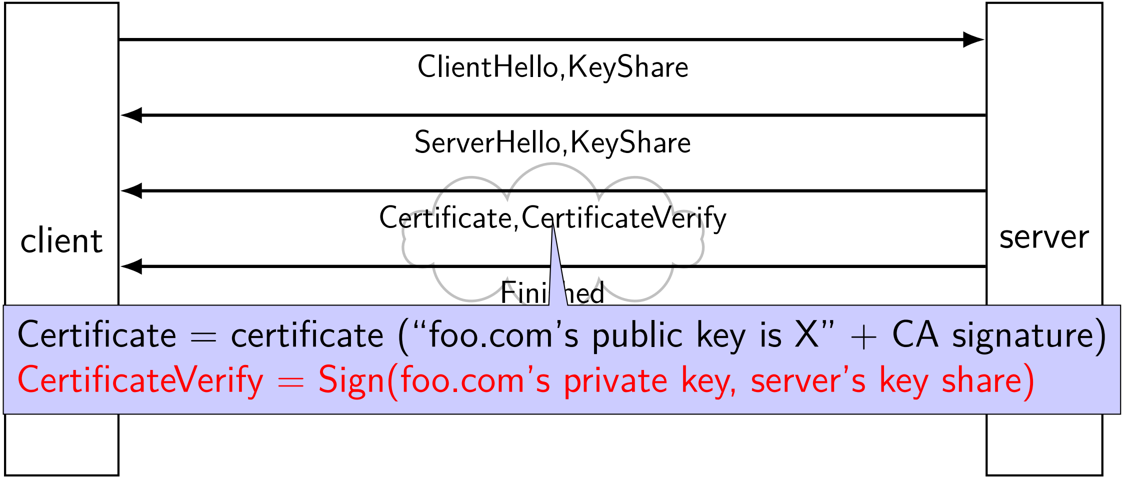
typical TLS handshake



typical TLS handshake



typical TLS handshake



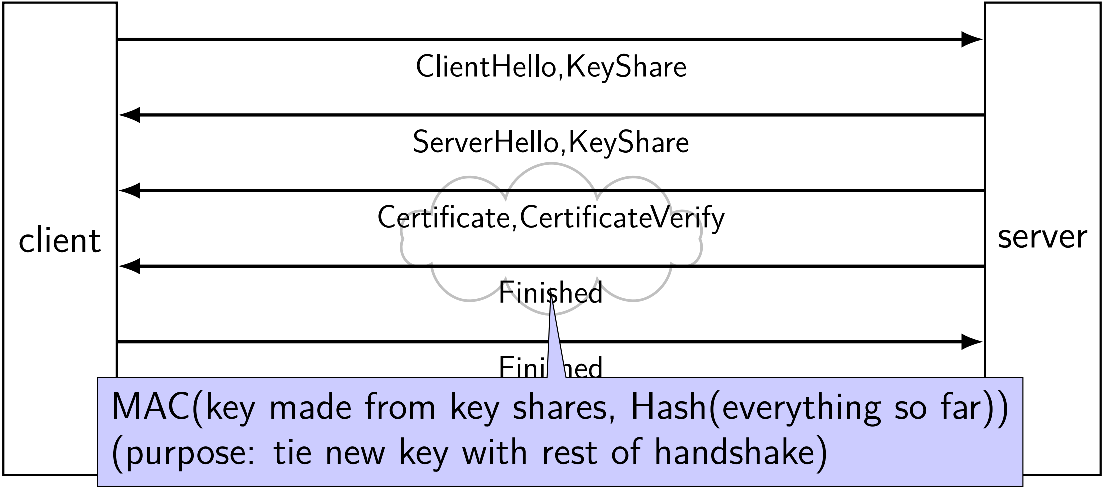
Certificate = certificate (“foo.com’s public key is X” + CA signature)

CertificateVerify = Sign(foo.com’s private key, server’s key share)

typical TLS handshake

MAC(key made from key shares, Hash(everything so far))
(purpose: tie new key with rest of handshake)

typical TLS handshake



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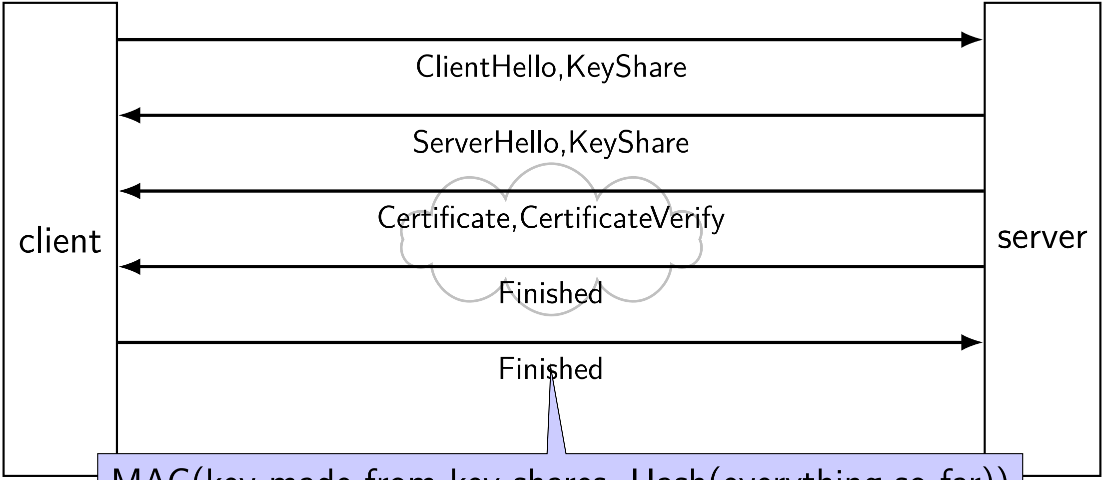

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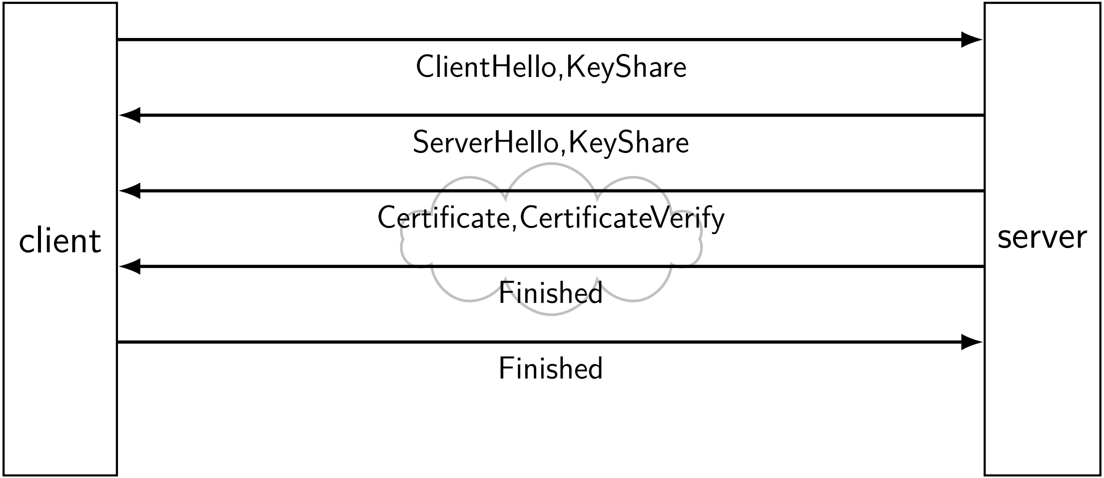
typical TLS handshake



TLS: after handshake

use key shares results to get **several** keys

 take hash(something + shared secret) to derive each key

separate keys for each direction (server $\rightarrow$ client and vice-versa)

often separate keys for encryption and MAC

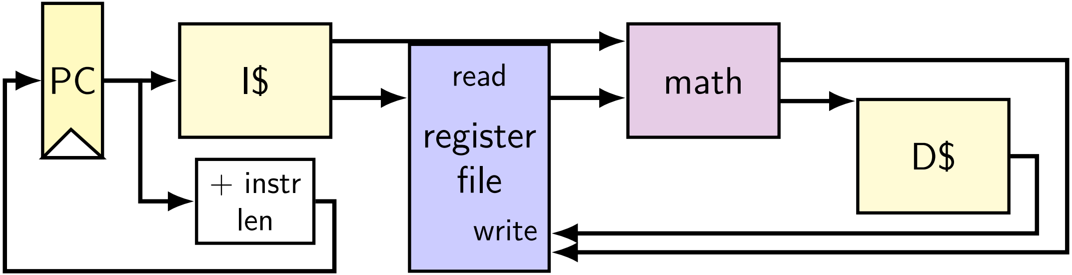
later messages use encryption + MAC + nonces

cryptographic tools

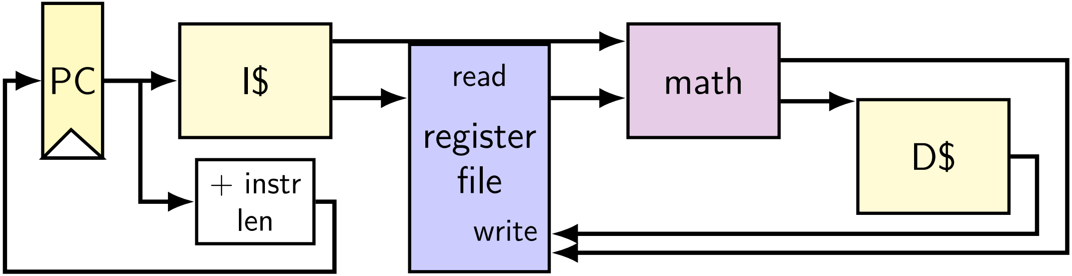
other file/disk encryption or email encryption often combine several techniques like TLS

- even if “only for encryption”

simple CPU



running instructions

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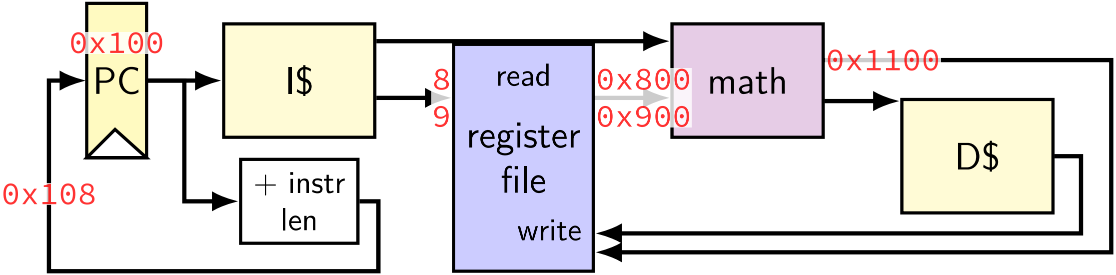
0x100: addq %r8, %r9
0x108: movq 0x1234(%r10), %r11
```

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

running instructions

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%r9: 0x1100
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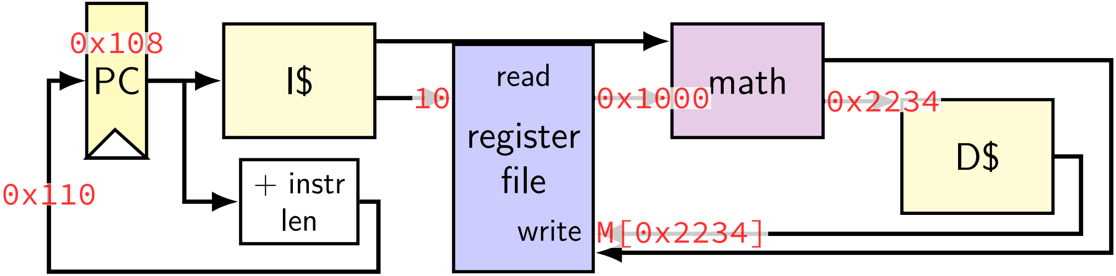
%r11: 0x1100
...
```

running instructions

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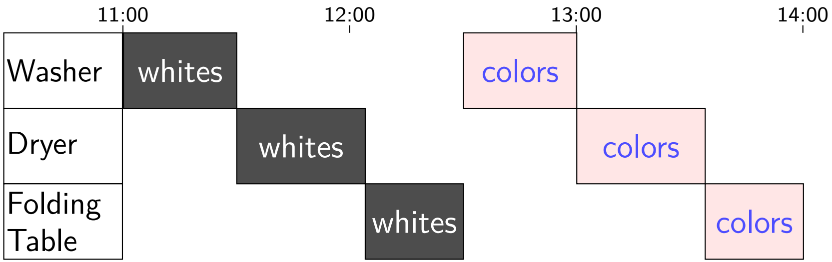
```
...
%r8: 0x800
%r9: 0x1100
%r10: 0x1000
%r11: M[0x2234]
...
```

Human pipeline: laundry



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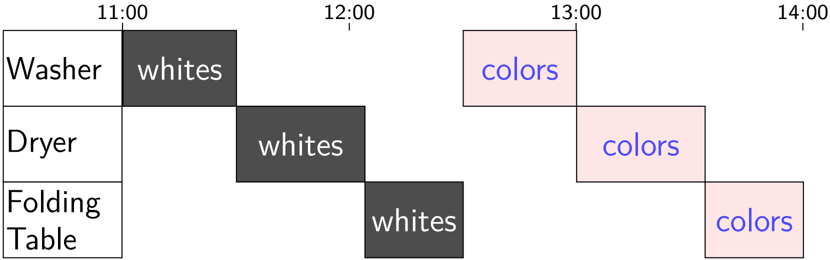
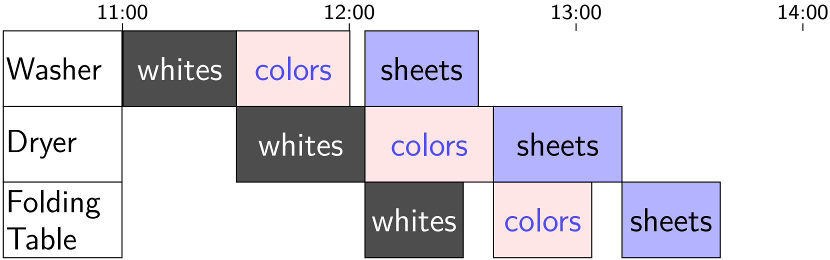
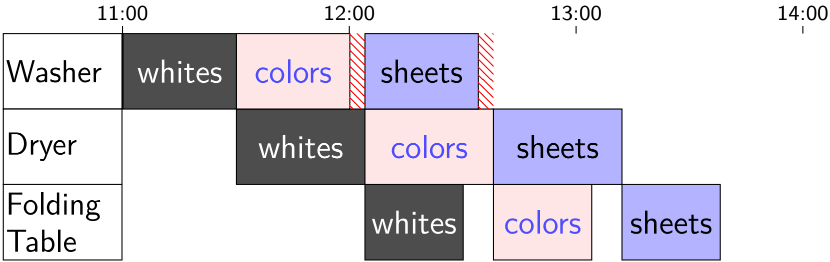
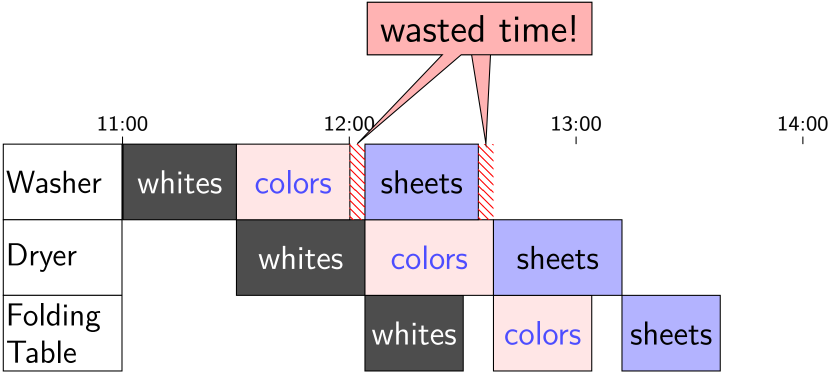




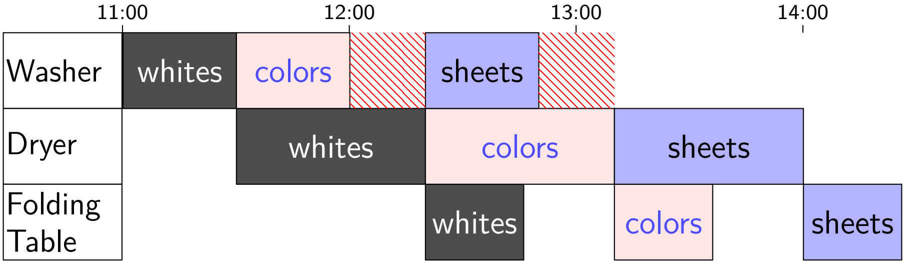
Waste (1)


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

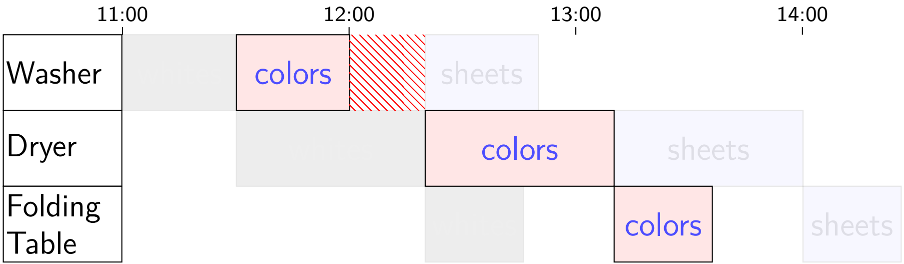
Waste (1)


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

Waste (2)


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

Latency — Time for One



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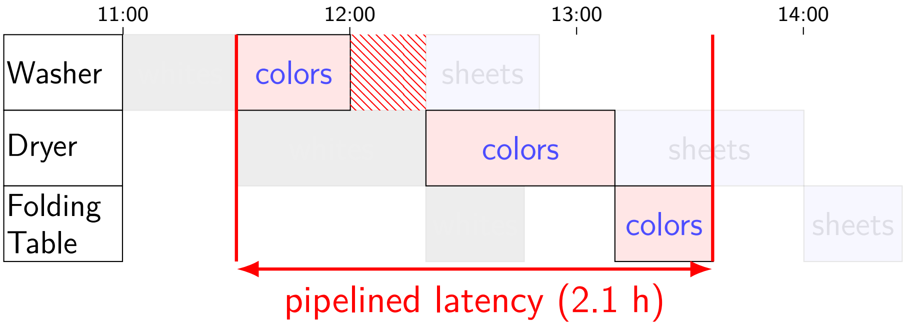

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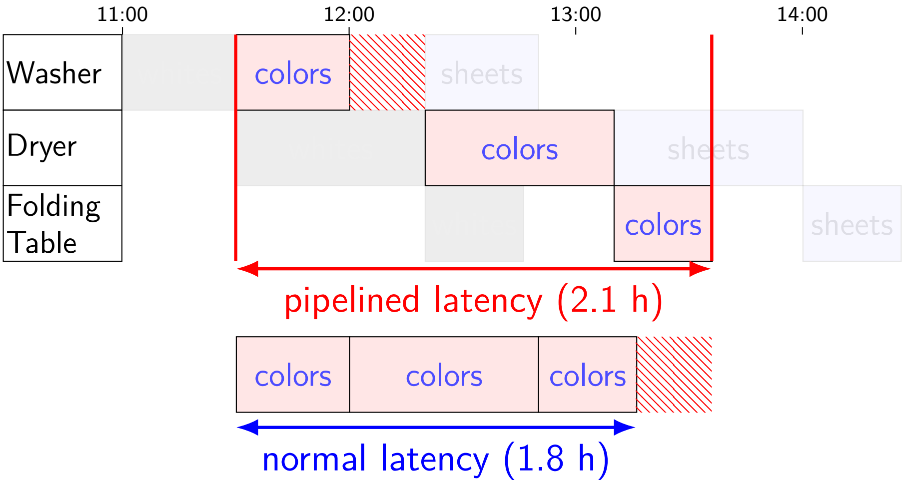
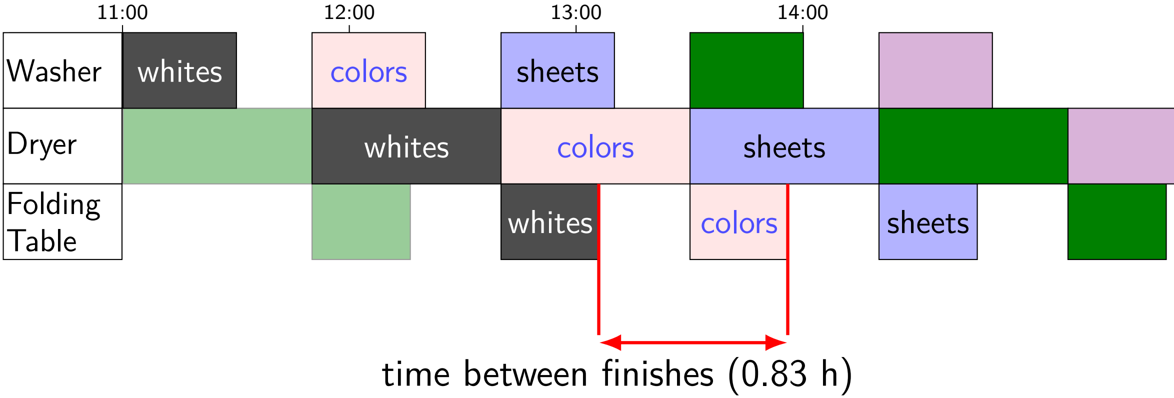


Throughput — Rate of Many



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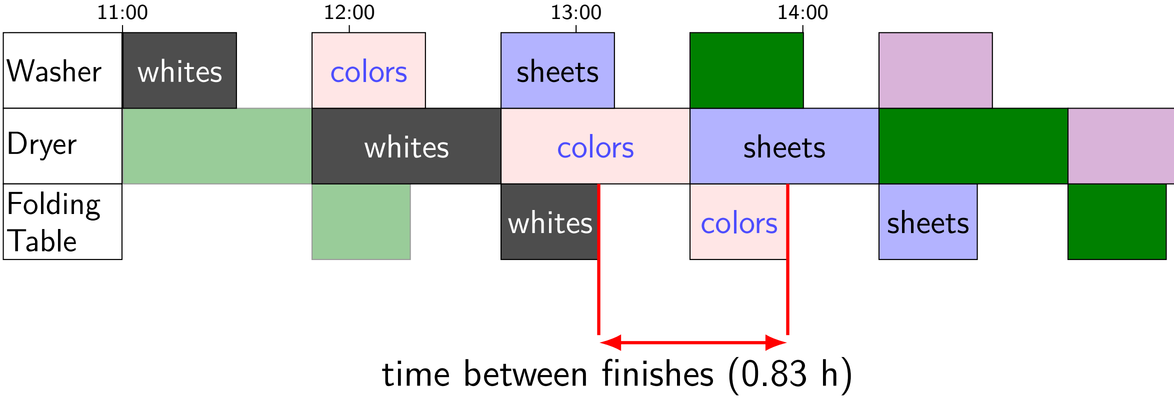
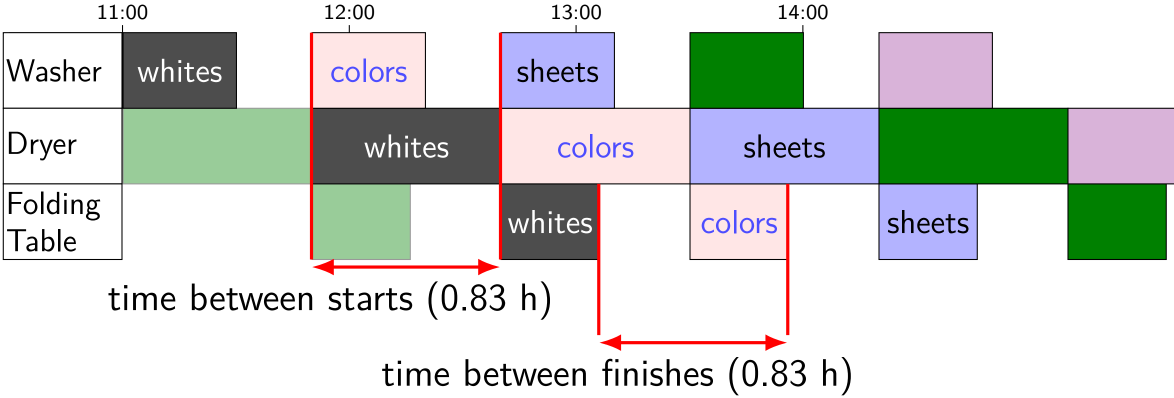


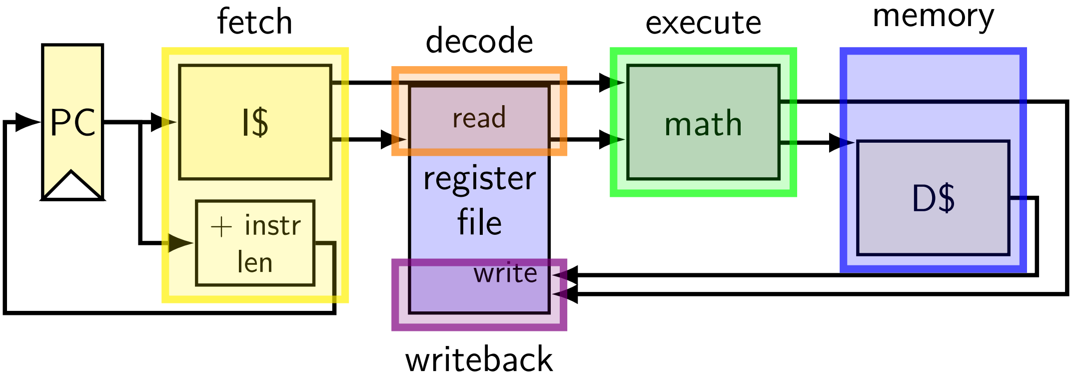
$$\frac{1\ \text{load}}{0.83\text{h}} = \color{red}{1.2\ \text{loads}/\text{h}}$$

Throughput — Rate of Many



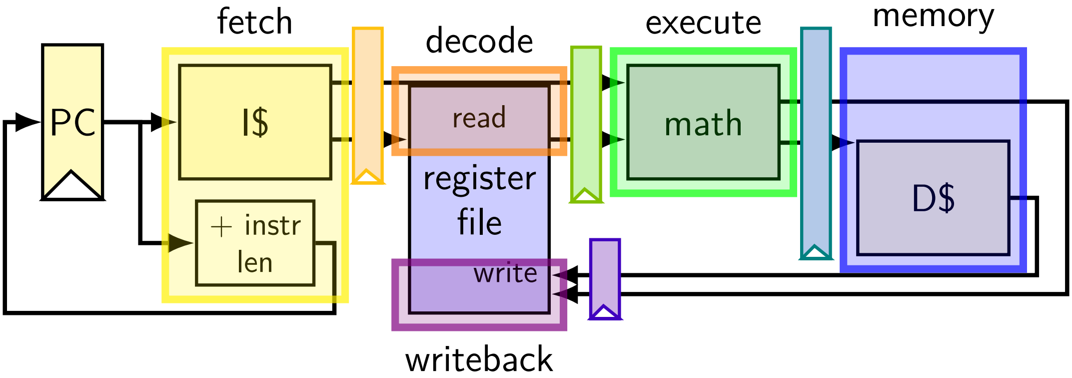
$$\frac{1\text{ load}}{0.83\text{h}} = \color{red}{1.2\text{ loads/h}}$$

adding stages (one way)



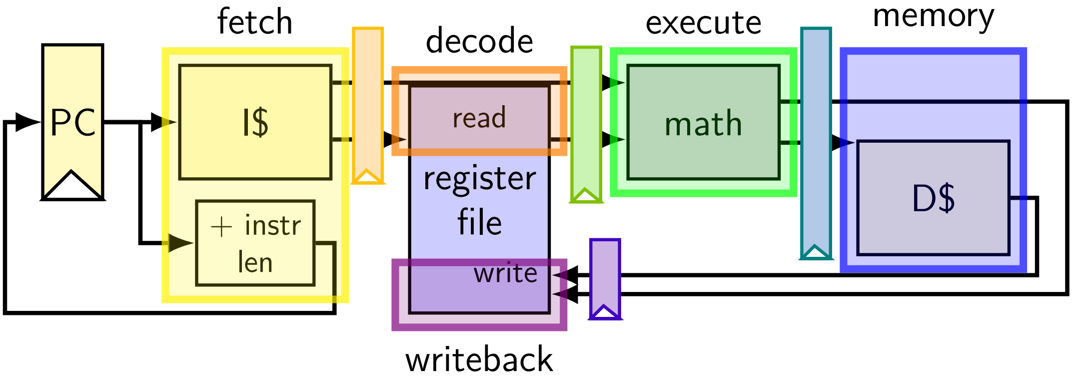
divide running instruction into steps
one way: fetch / decode / execute / memory / writeback

adding stages (one way)



add 'pipeline registers' to hold values from instruction

running some instructions



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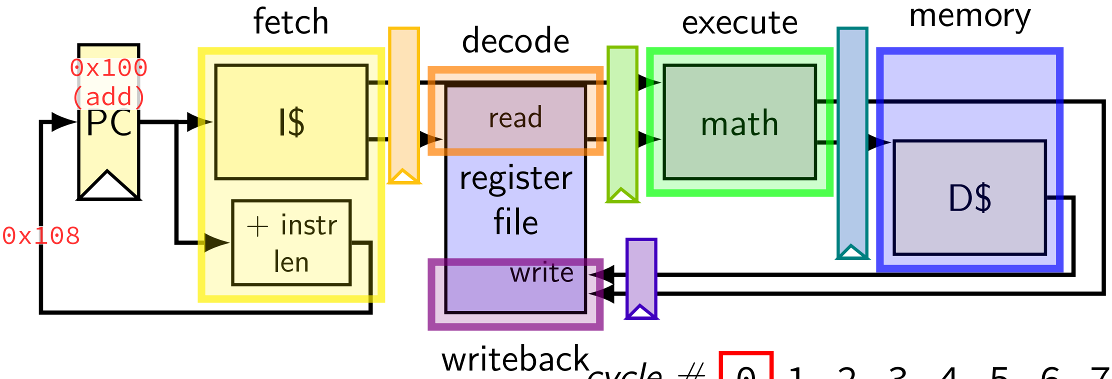
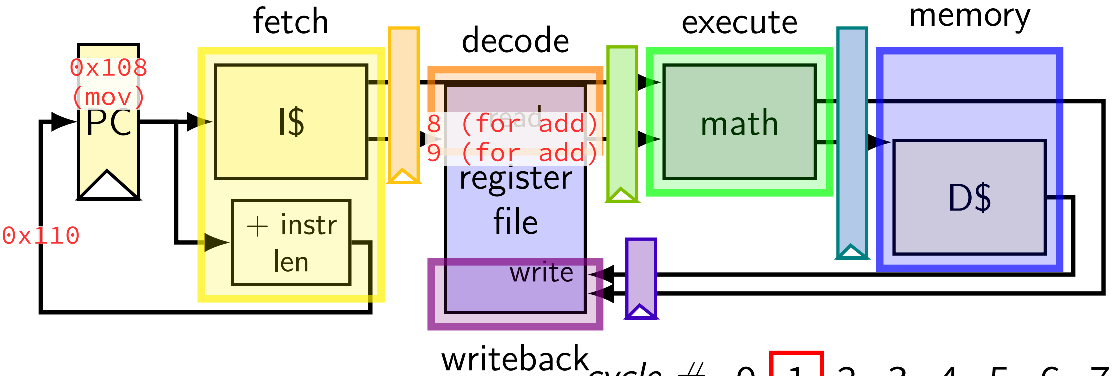



```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: xor %r12, %r13
```

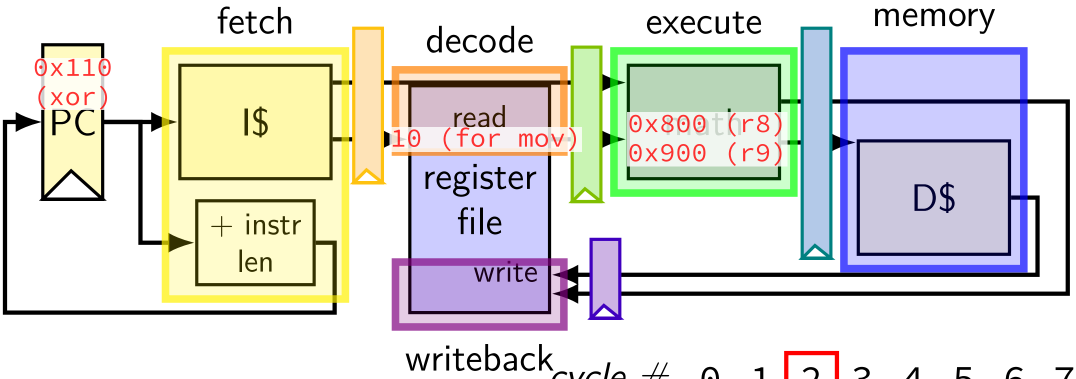
cycle #	0	1	2	3	4	5	6	7	8
0x100	F	D	E	M	W				
0x108		F	D	E	M	W			
0x110			F	D	E	M	W		

running some instructions



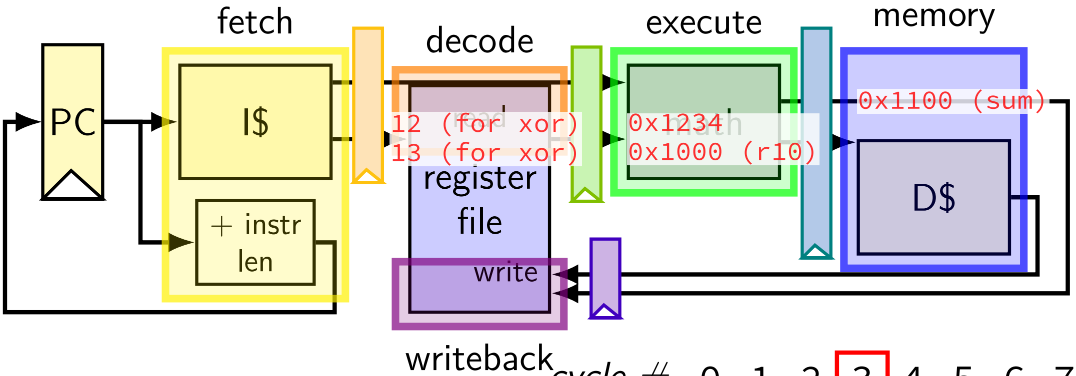
cycle #	0	1	2	3	4	5	6	7	8
0x100: add %r8, %r9	F	D	E	M	W				
0x108: mov 0x1234(%r10), %r11		F	D	E	M	W			
0x110: xor %r12, %r13			F	D	E	M	W		

running some instructions



cycle #	0	1	2	3	4	5	6	7	8
0x100: add %r8, %r9	F	D	E	M	W				
0x108: mov 0x1234(%r10), %r11		F	D	E	M	W			
0x110: xor %r12, %r13			F	D	E	M	W		

running some instructions

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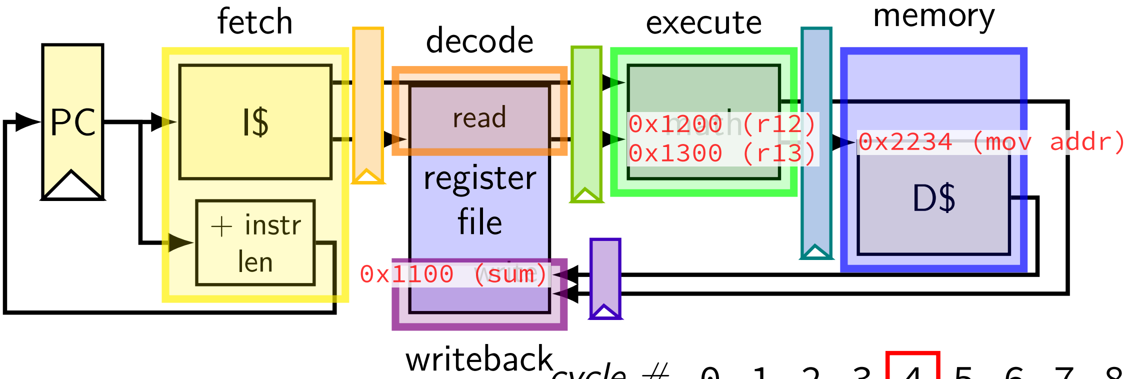
```

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



	cycle #	0	1	2	3	4	5	6	7	8
`0x100: add %r8, %r9`		F	D	E	M	W				
`0x108: mov 0x1234(%r10), %r11`			F	D	E	M	W			
`0x110: xor %r12, %r13`				F	D	E	M	W		

why registers?

example: fetch/decode

need to store current instruction somewhere …while fetching next one

exercise: throughput/latency (1)

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

cycle #	0	1	2	3	4	5	6	7	8
0x100	F	D	E	M	W				
0x108		F	D	E	M	W			
				…					

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: …
```

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

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: …
```

cycle #	0	1	2	3	4
	F	D	E	M	W
		F	D	E	M
				…	

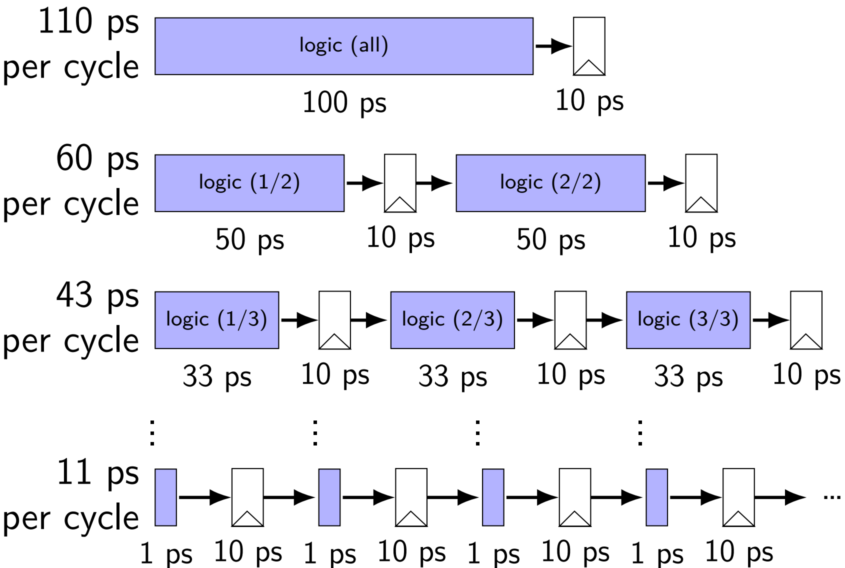
```
0x100: add %r8, %r9
0x108: mov 0x1234(%r10), %r11
0x110: …
```

cycle #	0	1	2	3	4	5	6	7	8	
	F1	F2	D1	D2	E1	E2	M1	M2	W1	W
		F1	F2	D1	D2	E1	E2	M1	M2	W
				…						

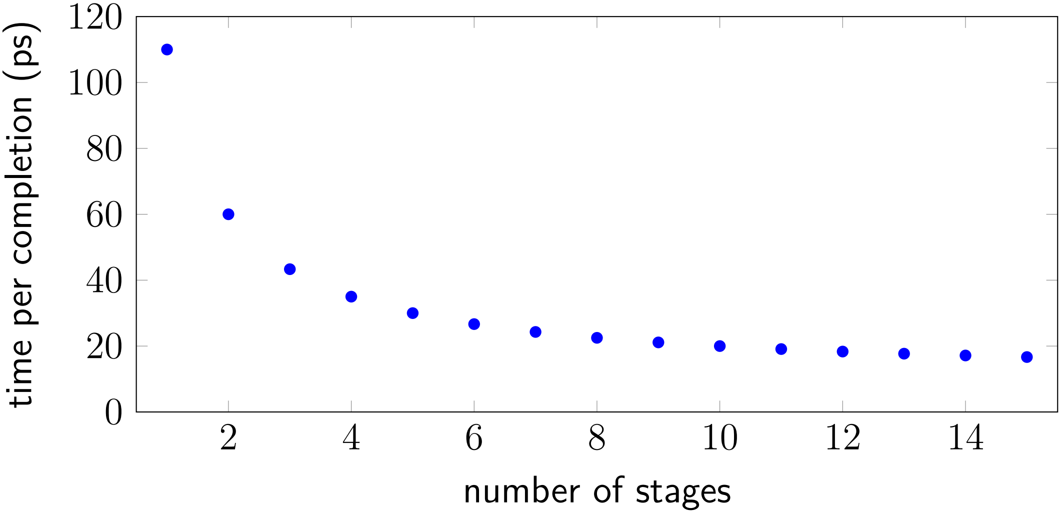
double number of pipeline stages (to 10) + decrease cycle time from 500 ps to 250 ps — throughput?

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

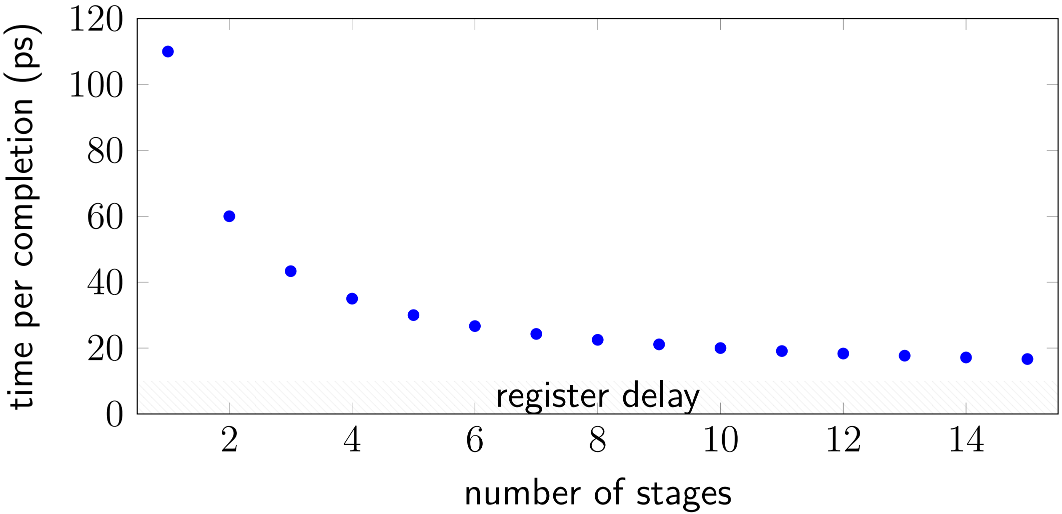
diminishing returns: register delays



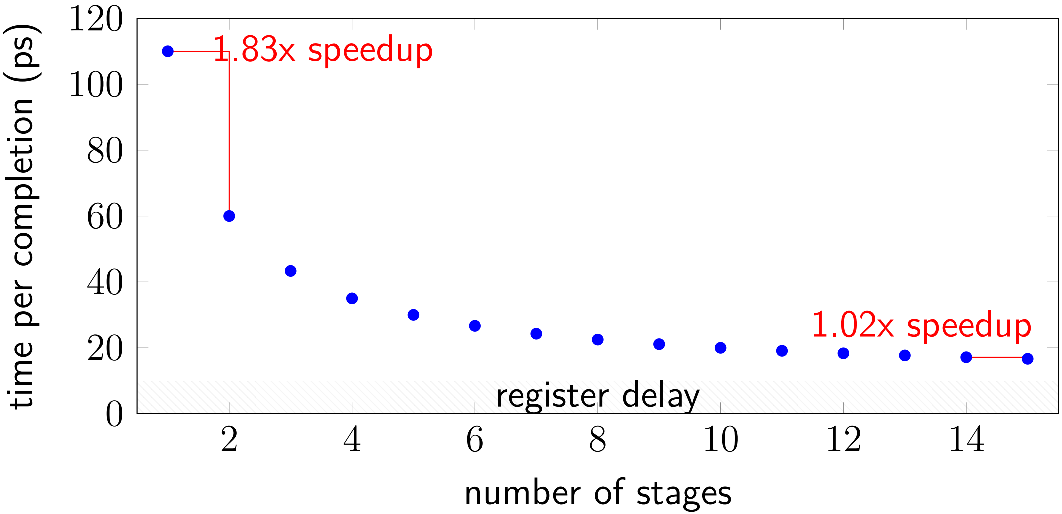
diminishing returns: register delays



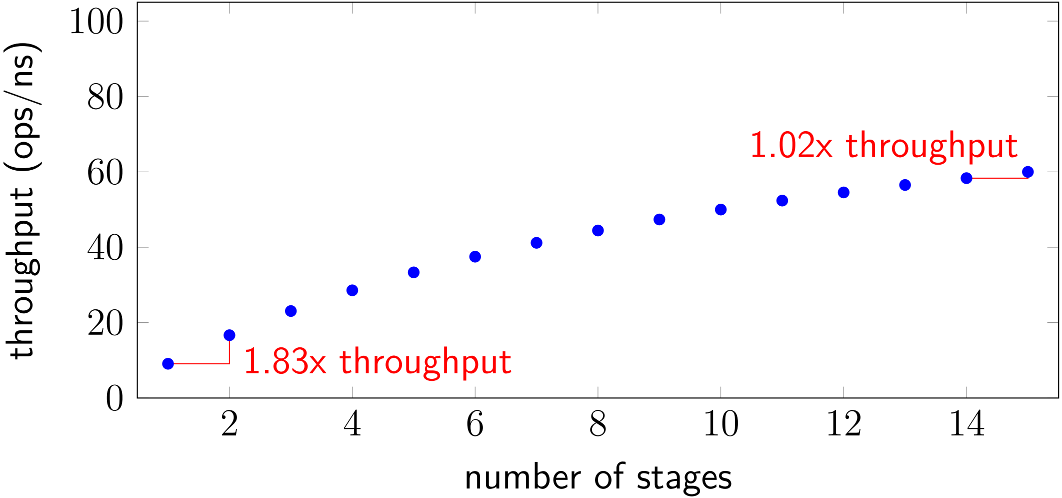
diminishing returns: register delays



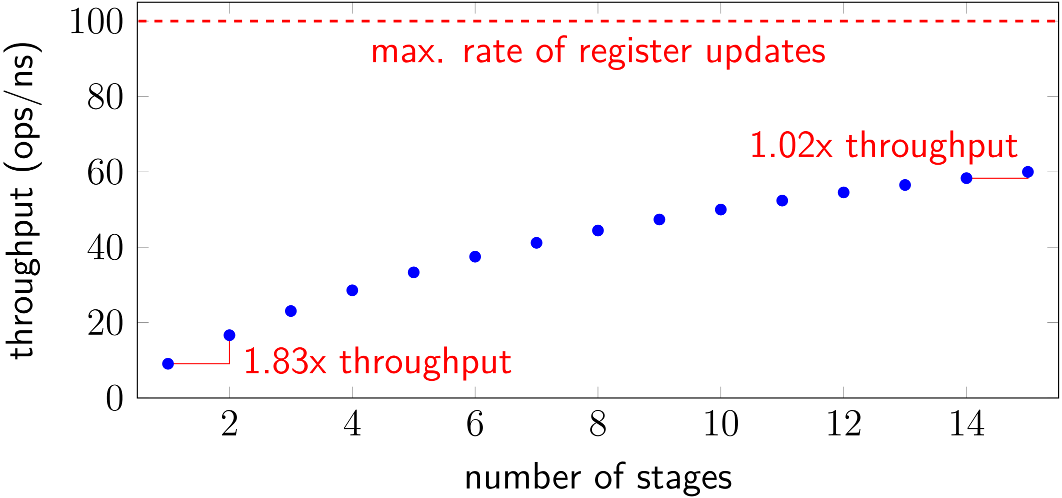
diminishing returns: register delays



diminishing returns: register delays



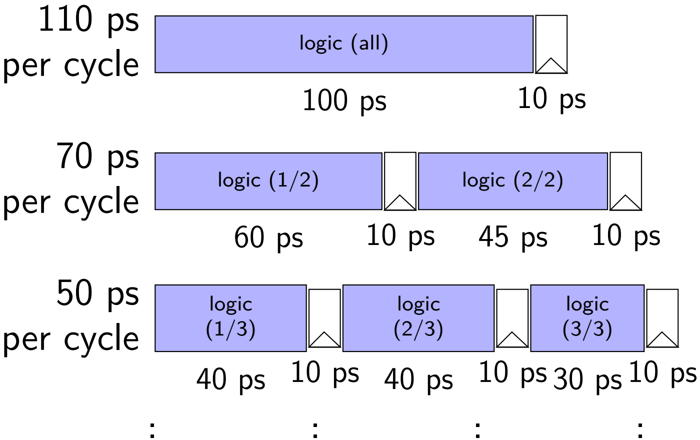
diminishing returns: register delays



diminishing returns: uneven split

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

Probably not...



diminishing returns: uneven split

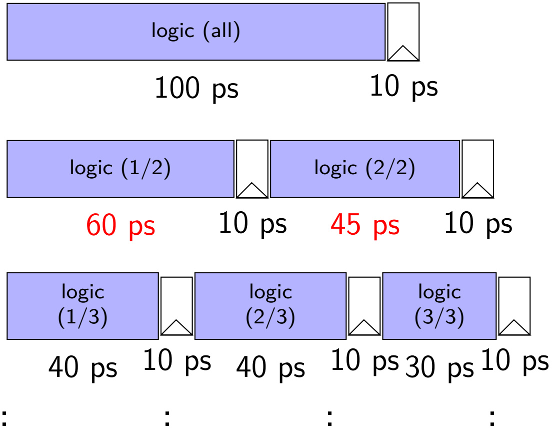
Can we split up some logic (e.g. adder) arbitrarily?

Probably not...

110 ps
per cycle

70 ps
per cycle

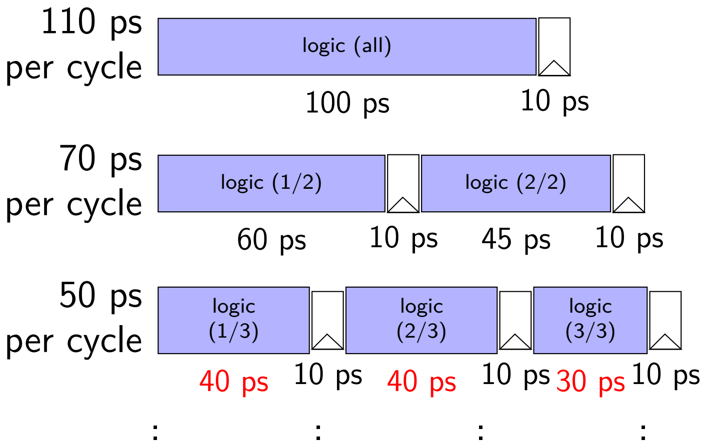
50 ps
per cycle



diminishing returns: uneven split

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

Probably not...



backup slides

key agreement and asym. encryption

can construct public-key encryption from key agreeement

private key: generated random value Y

public key: key share generated from that Y

key agreement and asym. encryption

can construct public-key encryption from key agreeement

private key: generated random value Y

public key: key share generated from that Y

PE(public key, message) =

generate random value Z
combine with public key to get shared secret
use symmetric encryption + MAC using shared secret as keys
output: (key share generated from Z) (sym. encrypted data) (mac tag)

key agreement and asym. encryption

can construct public-key encryption from key agreeement

private key: generated random value Y

public key: key share generated from that Y

PE(public key, message) $=$

generate random value Z
combine with public key to get shared secret
use symmetric encryption $+$ MAC using shared secret as keys
output: (key share generated from Z) (sym. encrypted data) (mac tag)

PD(private key, message) $=$

extract (key share generated from Z)
combine with private key to get shared secret, ...

random numbers

need a lot of keys that no one else knows

common task: choose a *random* number

question: what does *random* mean here?

cryptographically secure random numbers

security properties we might want for random numbers:

attacker cannot guess (part of) number better than chance

knowing prior 'random' numbers shouldn't help predict next 'random' numbers

compromising machine now shouldn't reveal older random numbers

exercise: how to generate?

/dev/urandom

Linux kernel random number generator

collects “entropy” from hard-to-predict events

- e.g. exact timing of I/O interrupts
- e.g. some processor’s built-in random number circuit

turned into as many random bytes as you want

turning 'entropy' into random bytes

lots of ways to do this; one (rough/incomplete) idea:

internal variable *state*

to add 'entropy'

state $\leftarrow$ SecureHash(state + entropy)

to extract value:

random bytes $\leftarrow$ SecureHash(1 + state)
give bytes that can't be reversed to compute state

state $\leftarrow$ SecureHash(2 + state)
change state so attacker can't take us back to old state if compromised

things modern TLS usually does

(not all these properties provided by all TLS versions and modes)

confidentiality/authenticity

- server = one ID'd by certificate
- client = same throughout whole connection

forward secrecy

- can't decrypt old conversations (data for KeyShares is temporary)

fast

- most communication done with more efficient symmetric ciphers
- 1 set of messages back and forth to setup connection

denial of service (1)

so far: worried about network attacker disrupting confidentiality/authenticity

what if we're just worried about just breaking things

well, if they control network, nothing we can do...

but often worried about less

denial of service (2)

if you just want to inconvenience...

attacker just sends lots of stuff to my server

my server becomes overloaded?

my network becomes overloaded?

but: doesn't this require a lot of work for attacker?

exercise: why is this often not a big obstacle

denial of service: asymmetry

work for attacker $>$ work for defender

how much computation per message?

- complex search query?
- something that needs tons of memory?
- something that needs to read tons from disk?

how much sent back per message?

resources for attacker $>$ resources of defender

how many machines can attacker use?

denial of service: reflection/amplification

instead of sending messages directly...attacker can send messages "from" you to third-party

third-party sends back replies that overwhelm network

example: short DNS query with lots of things in response

"amplification" =

third-party inadvertantly turns small attack into big one

firewalls

don't want to expose network service to everyone?

solutions:

- service picky about who it accepts connections from
- filters in OS on machine with services
- filters on router

later two called "firewalls"

firewall rules examples?

ALLOW tcp port 443 (https) FROM everyone

ALLOW tcp port 22 (ssh) FROM my desktop's IP address

BLOCK tcp port 22 (ssh) FROM everyone else

ALLOW from address X to address Y

...

network security summary (1)

communicating securely with math

- secret value (shared key, public key) that attacker can't have
- symmetric: shared keys used for (de)encryption + auth/verify; fast
- asymmetric: public key used by any for encrypt + verify; slower
- asymmetric: private key used by holder for decrypt + sign; slower

protocol attacks — repurposing encrypt/signed/etc. messages

certificates — verifiable forwarded public keys

key agreement — for generated shared-secret "in public"

- publish key shares from private data
- combine private data with key share for shared secret

network security summary (2)

TLS: combine all cryptography stuff to make “secure channel”

denial-of-service — attacker just disrupts/overloads (not subtle)

firewalls

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