Network Applications: Operational Analysis; Load Balancing among Homogeneous Servers

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https://qiaoxiang.me/courses/cnns-xmuf22/index.shtml

10/11/2022

This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

Outline

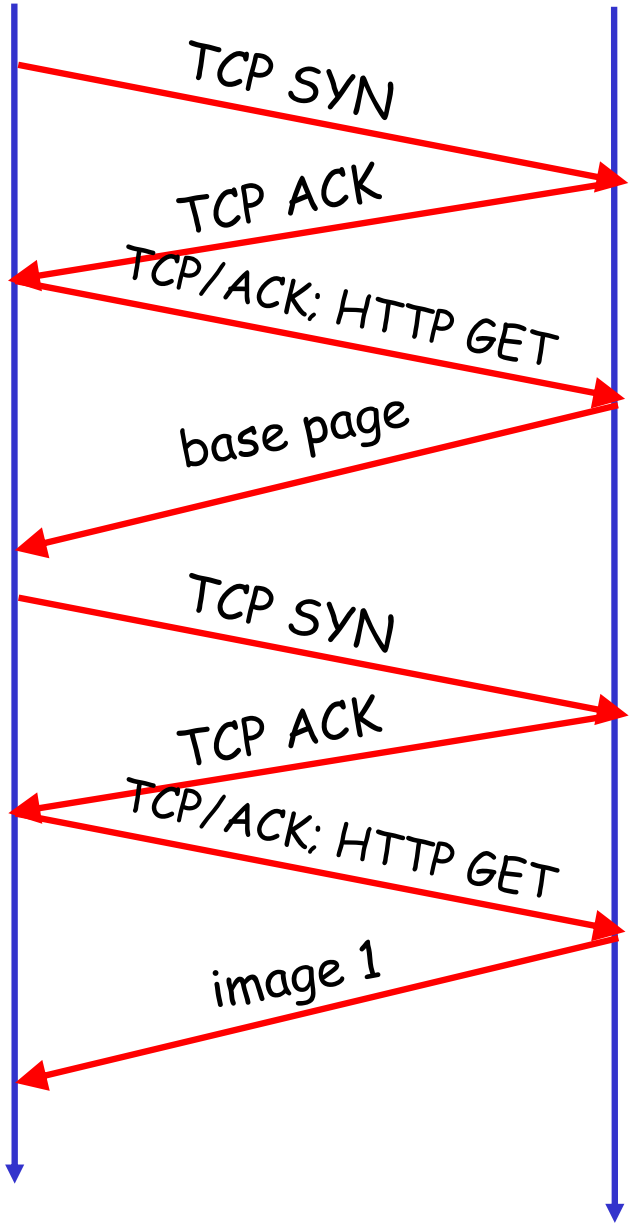
- Admin and recap
- HTTP
  - Basic design: HTTP 1.0
  - HTTP "acceleration"
  - Operational analysis
- Multi-servers
- Application overlays (peer-to-peer networks)

Admin

- Lab assignment 2 due Oct. 13

Recap: Latency of Basic HTTP/1.0

- >= 2 RTTs per object:
  - TCP handshake --- 1 RTT
  - client request and server responds --- at least 1 RTT (if object can be contained in one packet)



Recap: Substantial Efforts to Speedup HTTP/1.0

- Reduce the number of objects fetched [Browser cache]

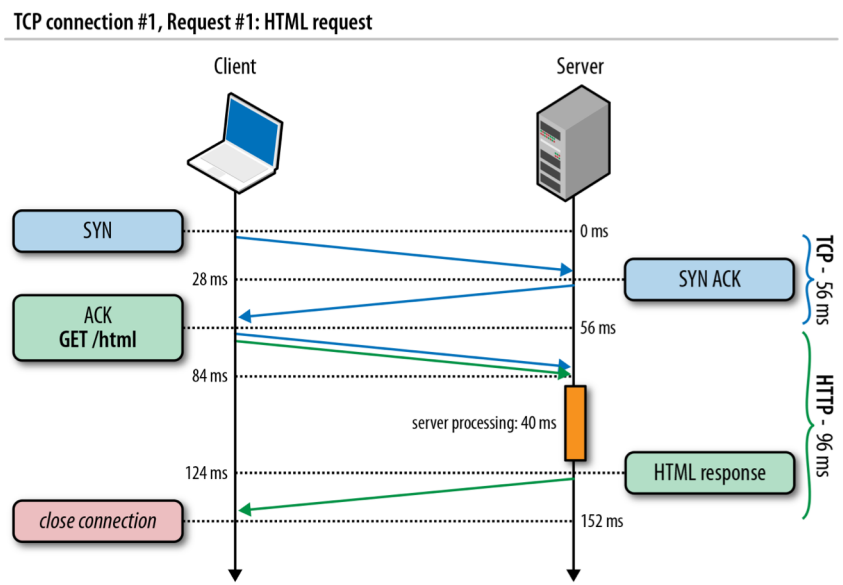
- Reduce data volume [Compression of data]
- Header compression [HTTP/2]

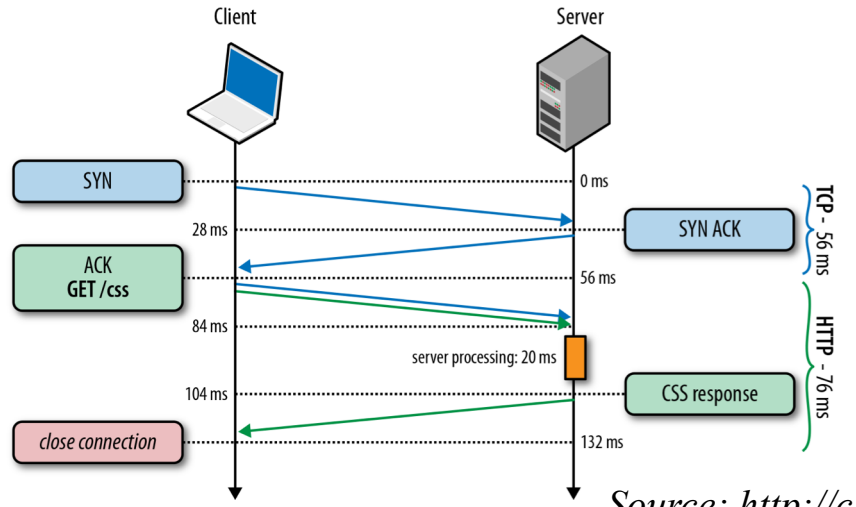
- Reduce the latency to the server to fetch the content [Proxy cache]
- Remove the extra RTTs to fetch an object [Persistent HTTP, aka HTTP/1.1]

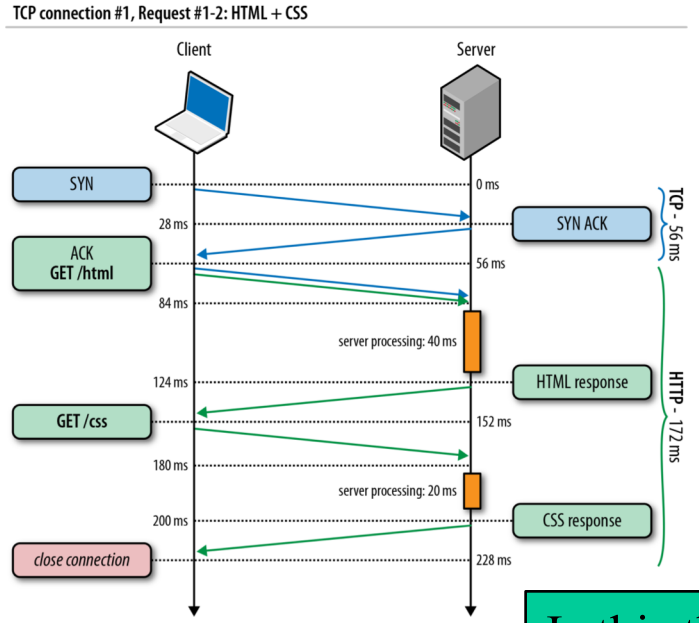
- Increase concurrency [Multiple TCP connections]
- Asynchronous fetch (multiple streams) using a single TCP [HTTP/2]

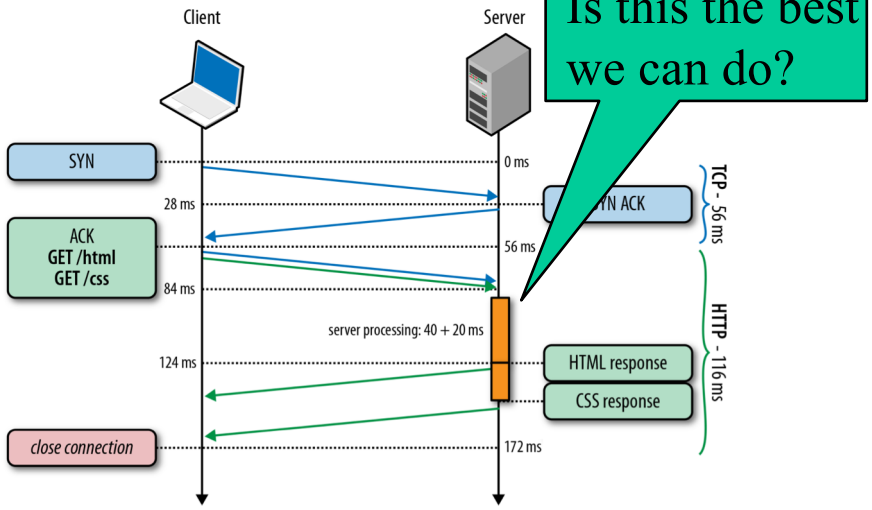
- Server push [HTTP/2]

Recap: HTTP/1.0, Keep-Alive, Pipelining



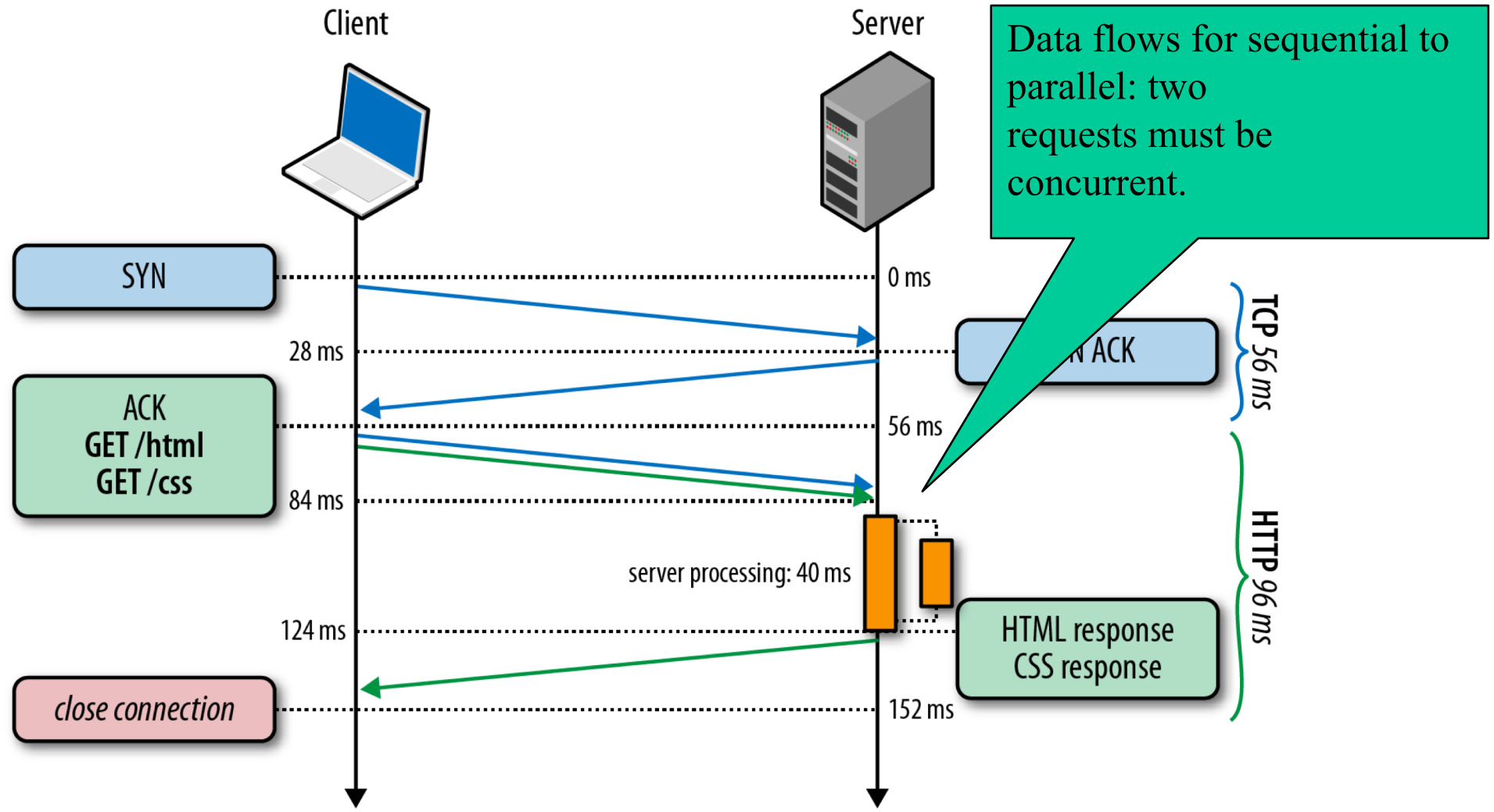






Source: http://chimera.labs.oreilly.com/books/1230000000545/ch11.html

HTTP/2 Basic Idea: Remove Head-of-Line Blocking in HTTP/1.1



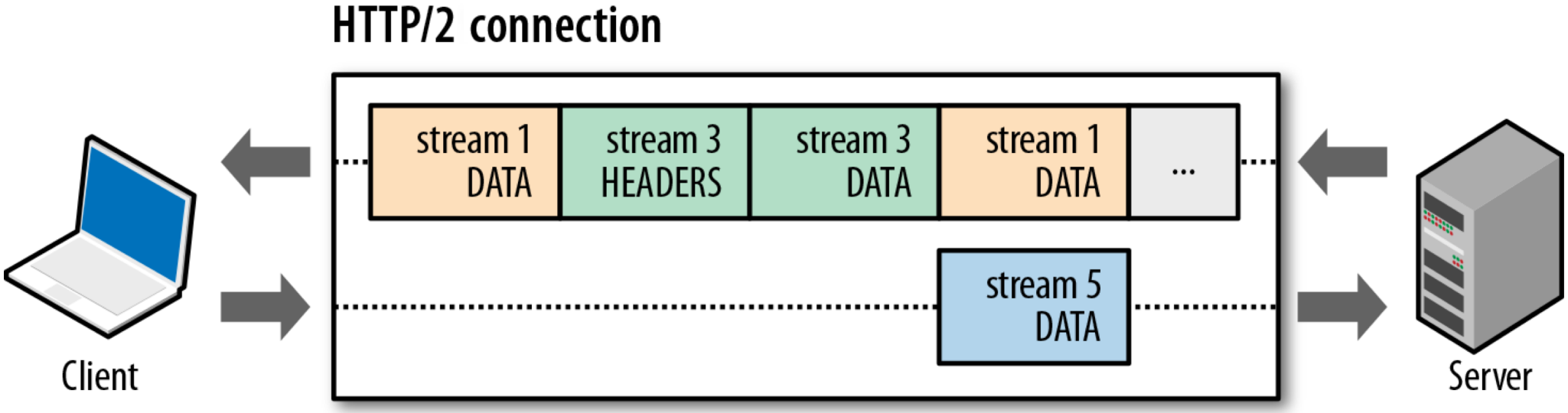
Demo: https://http2.akamai.com/demo

Source: http://chimera.labs.oreilly.com/books/1230000000545/ch11.html

Observing HTTP/2

- export SSLKEYLOGFILE=/tmp/keylog.txt
- Start Chrome, e.g.,
  - Mac: /Applications/Google Chrome.app/Contents/MacOS/Google Chrome
  - Ubuntu: firefox
- Visit HTTP/2 pages, such as https://www.tmall.com
- Wireshark:
  - Mac: Wireshark -> preferences -> protocol -> TSL
    (pre)-master-secret log file name
  - Ubuntu: edit -> perferences -> protocol -> SSL
    (pre)-master-secret log file name

HTTP/2 Design: Multi-Streams



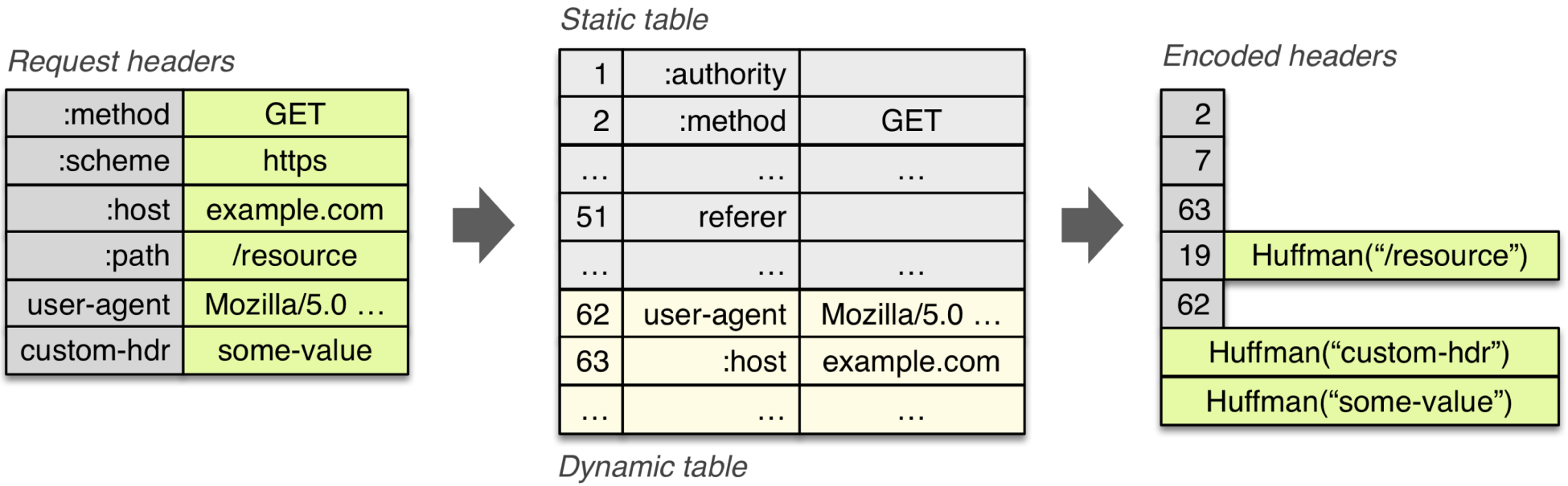
Bit	+0..7	+8..15	+16..23	+24..31
0	Length			Type
32	Flags			
40	R	Stream Identifier		
...	*Frame Payload*			

HTTP/2 Binary Framing

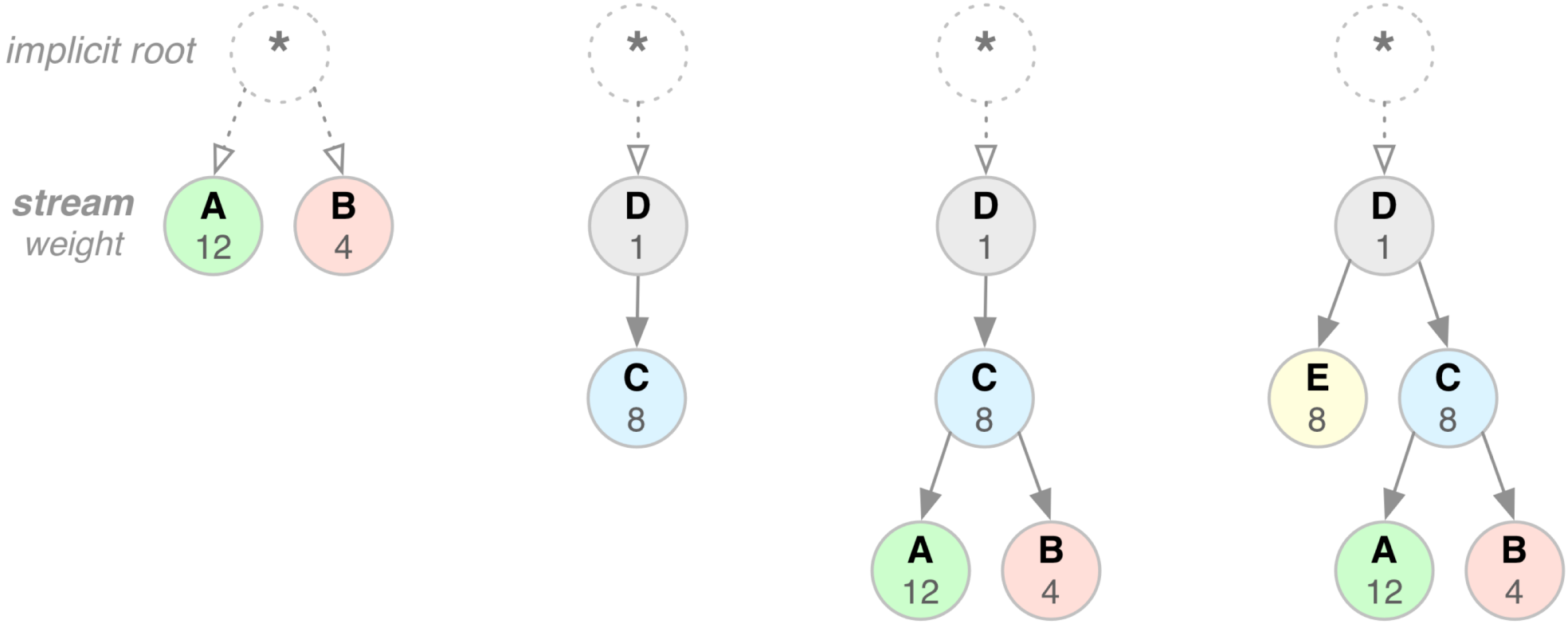
https://hpbn.co/http2/

https://tools.ietf.org/html/rfc7540

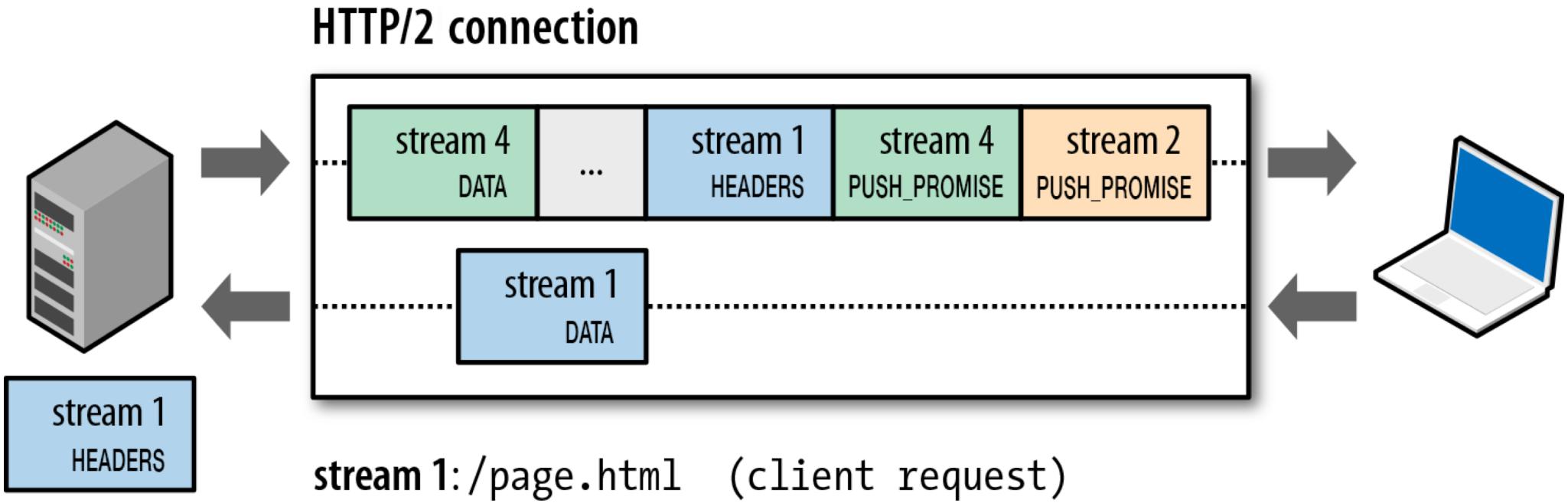
HTTP/2 Header Compression



HTTP/2 Stream Dependency and Weights



HTTP/2 Server Push

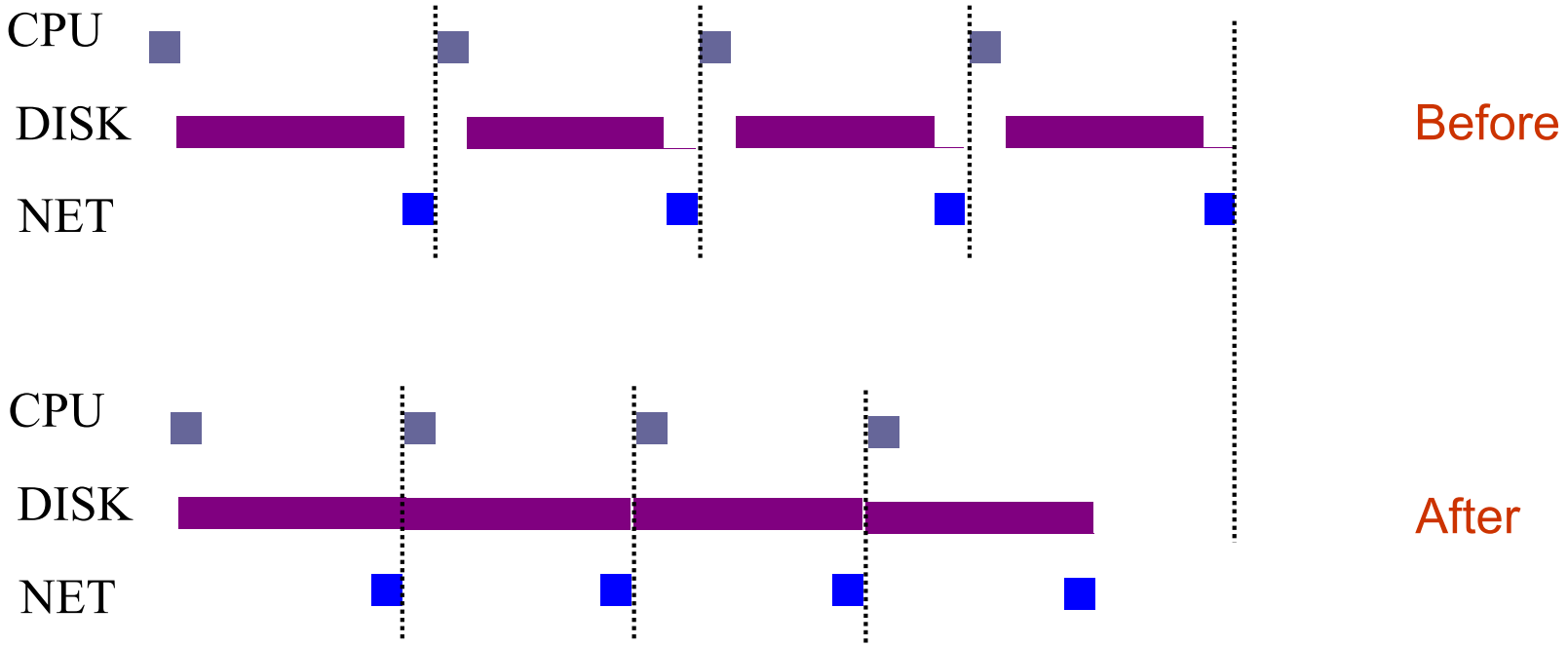


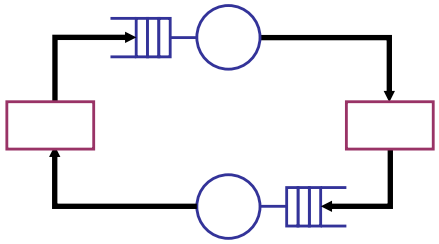
stream 1: /page.html (client request)
stream 2: /script.js (push promise)
stream 4: /style.css (push promise)

Outline

- Admin and recap
- HTTP
  - HTTP "acceleration"
  - *Operational analysis*

Goal: Best Server Design Limited Only by Resource Bottleneck

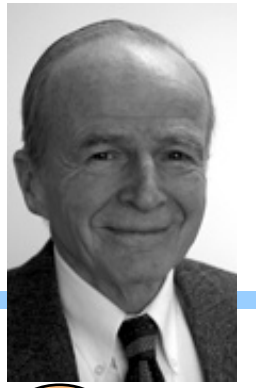




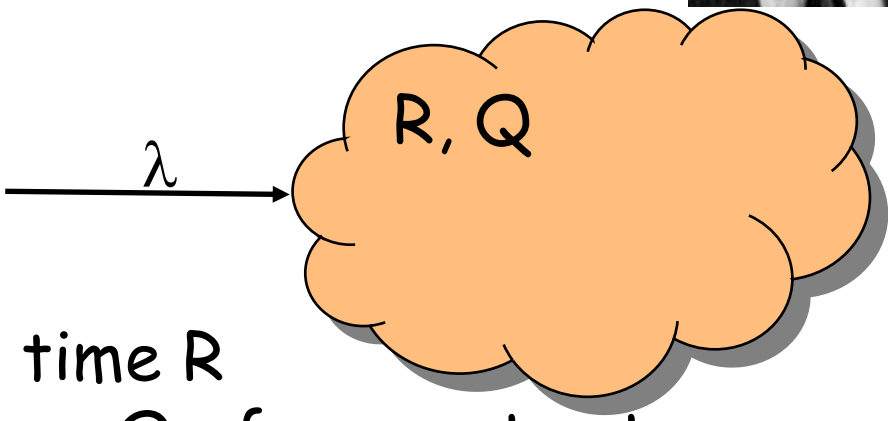
Some Questions

- When is CPU the bottleneck for scalability?
  - So that we need to add helper threads
- How do we know that we are reaching the limit of scalability of a single machine?
- These questions drive network server architecture design
- Some basic performance analysis techniques are good to have

Background: Little's Law (1961)



- For any system with no or (low) loss.
- Assume
  - mean arrival rate λ, mean time R at system, and mean number Q of requests at system



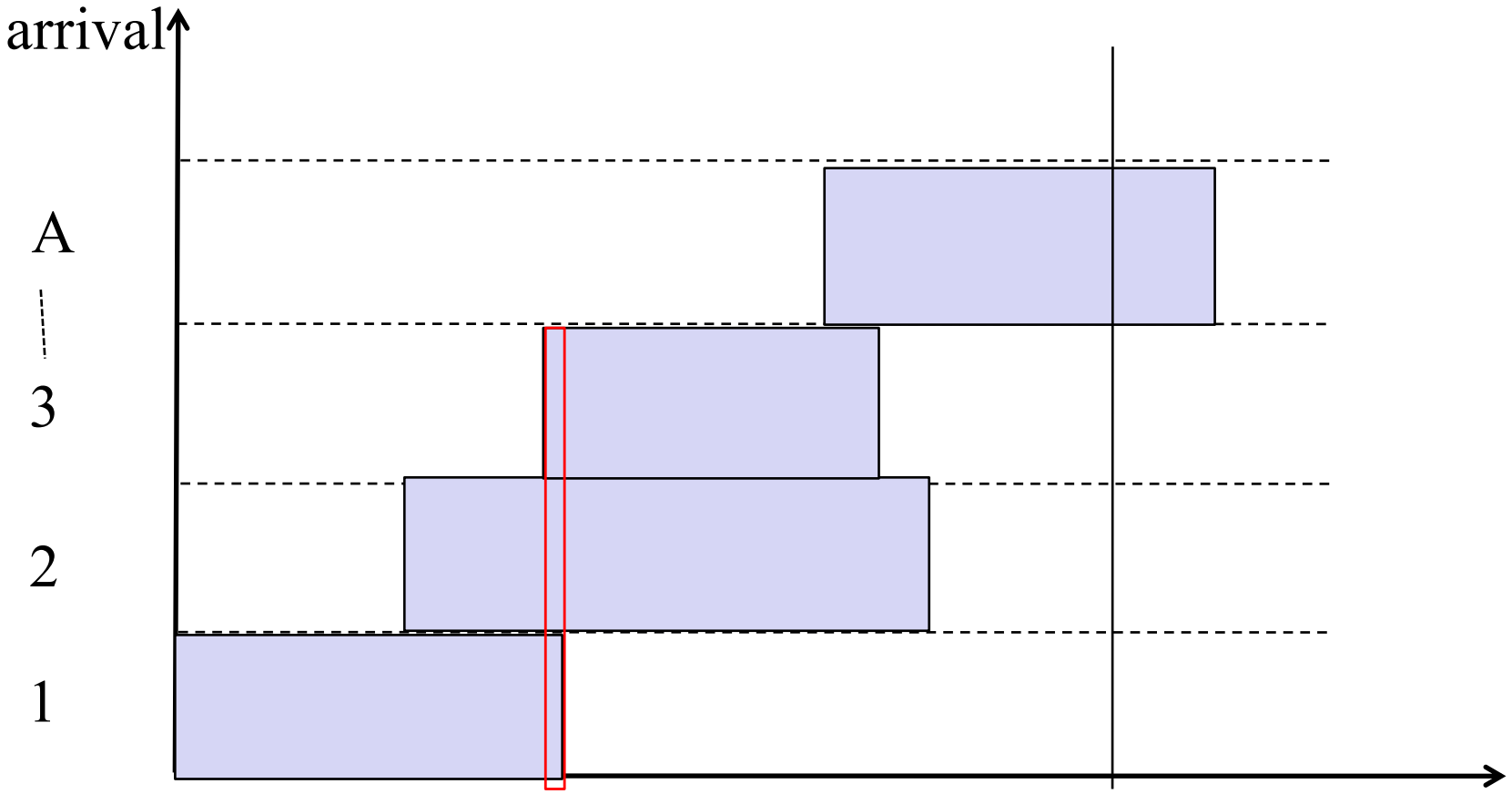
- Then relationship between Q, λ, and R:

$$Q = \lambda R$$

Example: XMU admits 3000 students each year, and mean time a student stays is 4 years, how many students are enrolled?

Little's Law: Proof

$$Q = \lambda R$$

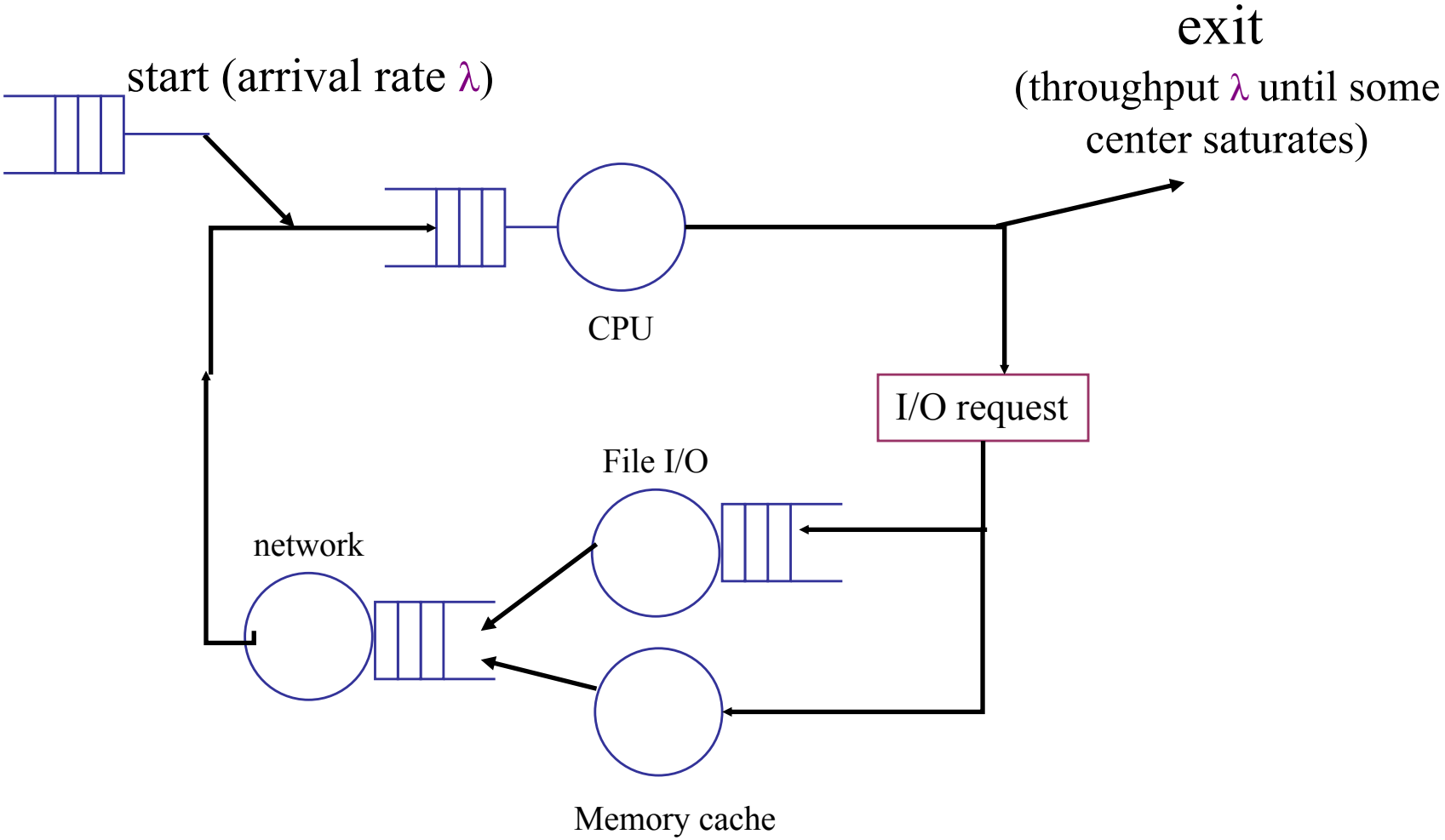


$$\lambda = \frac{A}{t} \quad R = \frac{Area}{A} \quad Q = \frac{Area}{t}$$

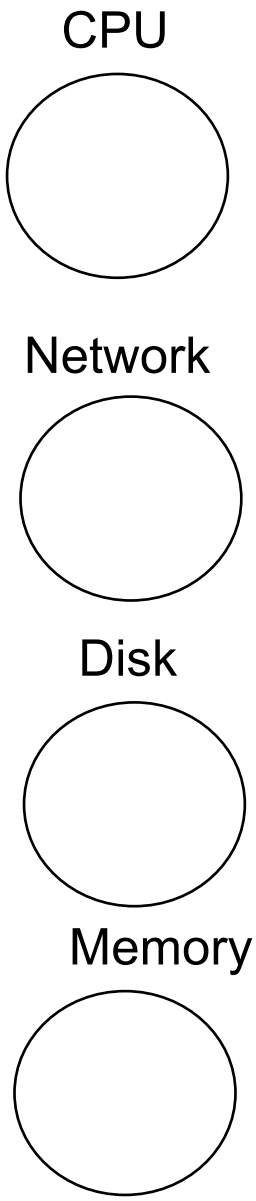
Operational Analysis

- Relationships that do not require any assumptions about the distribution of service times or inter-arrival times
  - Hence focus on measurements
- Identified originally by Buzen (1976) and later extended by Denning and Buzen (1978).
- We touch only some techniques/results
  - In particular, bottleneck analysis
- More details see linked reading

Under the Hood (An example FSM)



Operational Analysis: Resource Demand of a Request



V_{CPU} visits for S_{CPU} units of resource time per visit

V_{Net} visits for S_{Net} units of resource time per visit

V_{Disk} visits for S_{Disk} units of resource time per visit

V_{Mem} visits for S_{Mem} units of resource time per visit

Operational Quantities

- T: observation interval
- Bi: busy time of device i
- i = 0 denotes system

Ai: # arrivals to device i

Ci: # completions at device i

$$\text{arrival rate } \lambda_i = \frac{A_i}{T}$$

$$\text{Throughput } X_i = \frac{C_i}{T}$$

$$\text{Utilization } U_i = \frac{B_i}{T}$$

$$\text{Mean service time } S_i = \frac{B_i}{C_i}$$

Utilization Law

$$\text{Utilization } U_i = \frac{B_i}{T}$$

$$= \frac{C_i}{T}\frac{B_i}{C_i}$$

$$= X_i S_i$$

- The law is independent of any assumption on arrival/service process
- Example: Suppose NIC processes 125 pkts/sec, and each pkt takes 2 ms. What is utilization of the network NIC?

Deriving Relationship Between R, U, and S for one Device

- Assume flow balanced (arrival=throughput), Little's Law:

$$Q = \lambda R = XR$$

- Assume PASTA (Poisson arrival--memory-less arrival--sees time average), a new request sees Q ahead of it, and FIFO

$$R = S + QS = S + XRS$$

- According to utilization law, U = XS

$$R = S + UR \longrightarrow R = \frac{S}{1-U}$$

Forced Flow Law

- Assume each request visits device i Vi times

$$\text{Throughput } X_i = \frac{C_i}{T}$$

$$= \frac{C_i}{C_0}\frac{C_0}{T}$$

$$= V_i X$$

Bottleneck Device

$$\text{Utilization } U_i = X_i S_i$$

$$= V_i X S_i$$

$$= X V_i S_i$$

- Define Di = Vi Si as the total demand of a request on device i
- The device with the highest Di has the highest utilization, and thus is called the bottleneck

Bottleneck vs System Throughput

$$\text{Utilization } \mathrm{U}_i = XV_iS_i \leq 1$$

$$\rightarrow \; X \leq \frac{1}{D_{\max}}$$

Example 1

- A request may need
  - 10 ms CPU execution time
  - 1 Mbytes network bw
  - 1 Mbytes file access where
    - 50% hit in memory cache
- Suppose network bw is 100 Mbps, disk I/O rate is 1 ms per 8 Kbytes (assuming the program reads 8 KB each time)
- Where is the bottleneck?

Example 1 (cont.)

- CPU:
  - D_{CPU}= 10 ms (e.g. 100 requests/s)
- Network:
  - D_{Net} = 1 Mbytes / 100 Mbps = 80 ms (e.g., 12.5 requests/s)
- Disk I/O:
  - Ddisk = 0.5 * 1 ms * 1M/8K = 62.5 ms (e.g. = 16 requests/s)

Example 2

- A request may need
  - 150 ms CPU execution time (e.g., dynamic content)
  - 1 Mbytes network bw
  - 1 Mbytes file access where
    - 50% hit in memory cache
- Suppose network bw is 100 Mbps, disk I/O rate is 1 ms per 8 Kbytes (assuming the program reads 8 KB each time)
- Bottleneck: CPU -> use multiple threads to use more CPUs, if available, to avoid CPU as bottleneck

Interactive Response Time Law

- System setup
  - Closed system with N users
  - Each user sends in a request, after response, think time, and then sends next request
  - *Notation*
    - *Z = user think-time, R = Response time*
  - The total cycle time of a user request is *R+Z*

In duration T, #requests generated by each user: *T/(R+Z) requests*

Interactive Response Time Law

- *If N users and flow balanced:*

$$\text{System Throughput } X = \text{Toal\# req./T}$$

$$= \frac{N\frac{T}{R+Z}}{T}$$

$$= \frac{N}{R+Z}$$

$$R = \frac{N}{X} - Z$$

Bottleneck Analysis

$$X(N) \le \min\left\{\frac{1}{D_{\max}}, \frac{N}{D+Z}\right\}$$

$$R(N) \ge \max\{D, ND_{\max} - Z\}$$

- Here D is the sum of Di

Proof

$$X(N) \le \min\{\frac{1}{D_{\max}}, \frac{N}{D+Z}\}$$

$$R(N) \ge \max\{D, ND_{\max} - Z\}$$

- We know

$$X \le \frac{1}{D_{\max}} \qquad R(N) \ge D$$

Using interactive response time law:

$$R = \frac{N}{X} - Z \Longrightarrow R \ge ND_{\max} - Z$$

$$X = \frac{N}{R+Z} \Longrightarrow X \le \frac{N}{D+Z}$$

Summary: Operational Laws

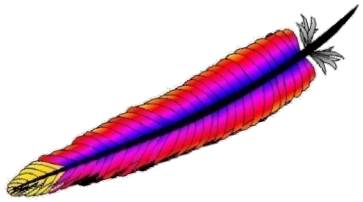
- Utilization law: U = XS
- Forced flow law: Xi = Vi X
- Bottleneck device: largest Di = Vi Si
- Little's Law: Qi = Xi Ri
- Bottleneck bound of interactive response (for the given closed model):

$$X(N) \le \min\{\frac{1}{D_{\max}}, \frac{N}{D+Z}\}$$

$$R(N) \ge \max\{D, ND_{\max} - Z\}$$

In Practice: Common Bottlenecks

- No more file descriptors
- Sockets stuck in TIME_WAIT
- High memory use (swapping)
- CPU overload
- Interrupt (IRQ) overload



[Aaron Bannert]

http://video.google.com/videoplay?docid=-6304964351441328559#

YouTube Design Alg.

```
while (true)
{
  identify_and_fix_bottlenecks();
  drink();
  sleep();
  notice_new_bottleneck();
}
```

Outline

- Admin and recap
- HTTP: single server
- Multiple network servers
  - *Why multiple network servers*

Why Multiple Servers?

- Scalability
  - Scaling beyond single server throughput
    - There is a fundamental limit on what a single server can
      - process (CPU/bw/disk throughput)
      - store (disk/memory)
  - Scaling beyond single geo location latency
    - There is a limit on the speed of light
    - Network detour and delay further increase the delay

Why Multiple Servers?

- Redundancy and fault tolerance
  - Administration/Maintenance (e.g., incremental upgrade)
  - Redundancy (e.g., to handle failures)

Why Multiple Servers?

- System/software architecture
  - Resources may be naturally distributed at different machines (e.g., run a single copy of a database server due to single license; access to resource from third party)
  - Security (e.g., front end, business logic, and database)
- Today we focus mostly on the first benefit, for homogeneous (replica) servers