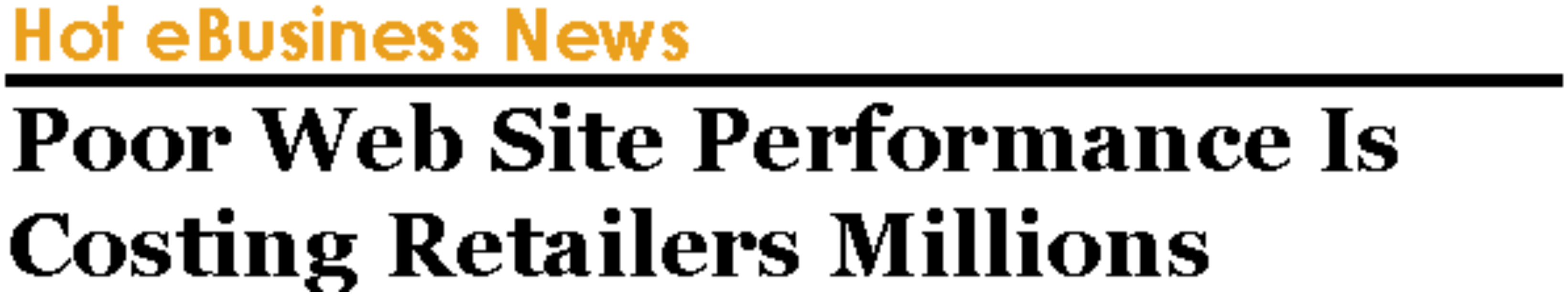
Lecture outline

- Capacity planning
  - Why?
  - What?
- Quality of service metrics
- Quantitative performance analysis ←→ Capacity Planning
- What techniques you will learn
- More quality of service metrics
- Single server queues

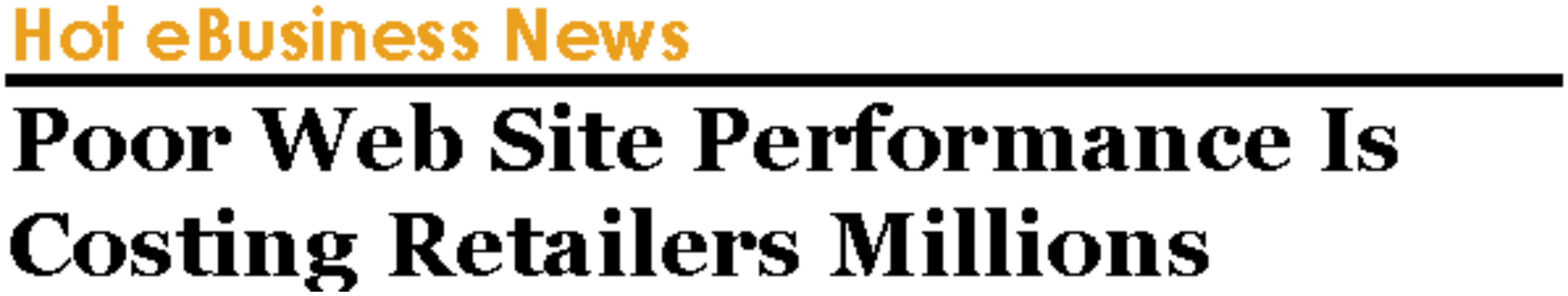
Why capacity planning?



Hot eBusiness News

Poor Web Site Performance Is Costing Retailers Millions

Why capacity planning?



Hot eBusiness News

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- The aim of capacity planning is to improve *performance* of computer systems by adding "*capacity*".
- What is performance?
- What is capacity?

Design of an e-Commerce systems

- Functional requirements
  - Product search, database management functions etc
    - Search correctness, algorithmic efficiency
- Computer and network security
- System performance
  - E.g. Can the computer system return database search within 20ms if there are 500 search queries per second?
    - If not, should we buy more servers? How many?

Workload

capacity

performance

- Can you think of other system performance requirements?

Web search engine

- Say you are planning a computer system which will host a search engine that rivals Google
- Current expected workload
  - 1000 searches per second
- Performance specification
  - Return results within 10ms
- What hardware and network should you use?
  - How many servers? How much disk space? Etc.
- What if workload is expected to increase by 50% in one year, can the system still maintain its performance?

performance

capacity

- Question: Can you think of other capacity parameters?

Capacity planning problems

- Focused on capacity planning of computer systems and networks
- Elements of a capacity planning problems
  - Given:
    - Workload specifications
    - Performance specifications
  - Find:
    - Capacity e.g. hardware or network requirements, personnel requirements etc.

- Capacity planning problems are everywhere in life. Can you come out with some capacity planning problems in real life? For each problem, you must identify the workload, performance and capacity parameters.

Capacity planning motivations

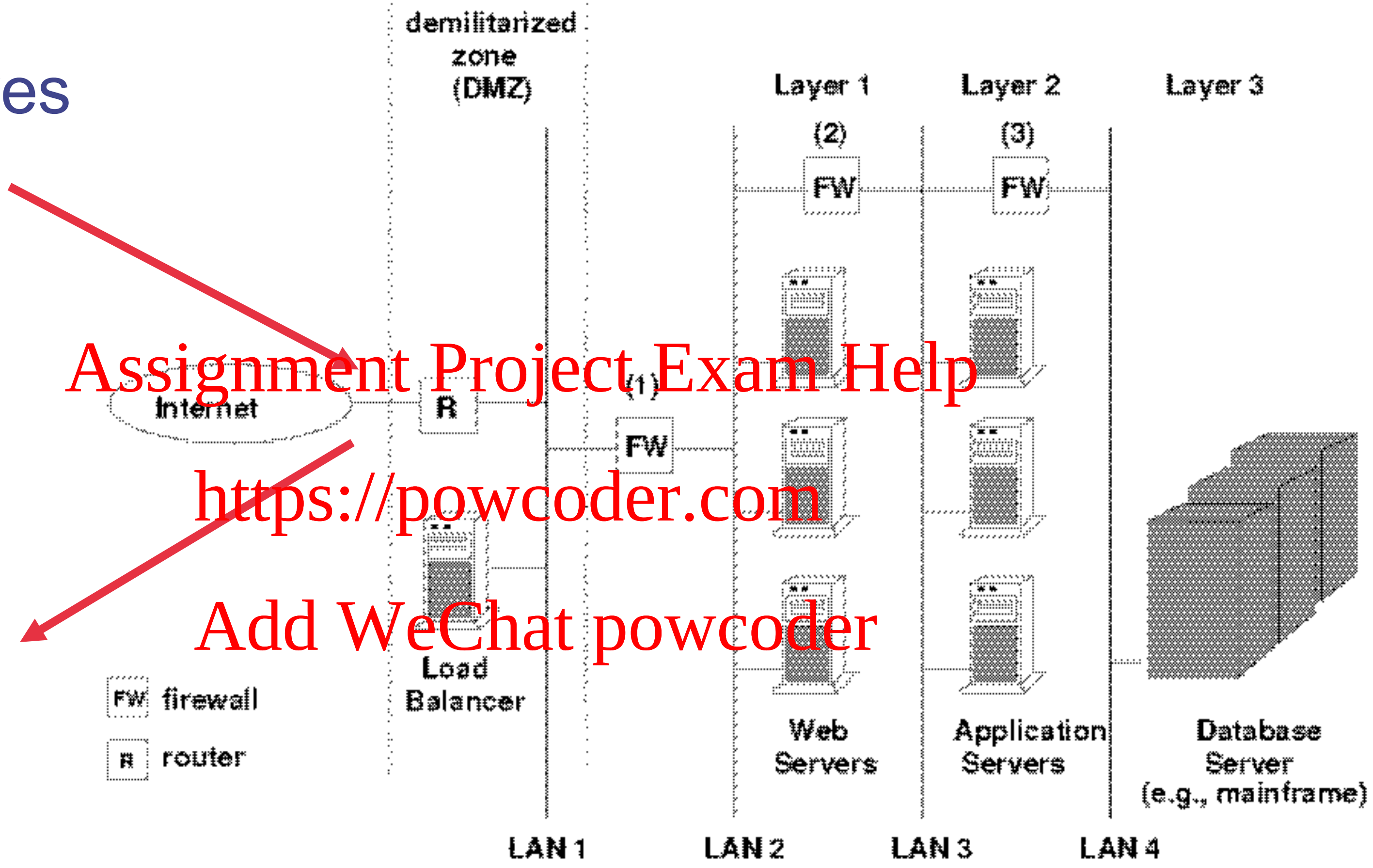
- Importance of performance
  - Can be life and death
    - *Availability* of critical infrastructure e.g. emergency services
  - Customer satisfaction
    - *Availability*
    - *Response time*
- The italicised terms are examples of computer system related performance metrics
  - Also known as Quality of service (QoS) metrics

Response time

- Response time
  - What is it? (Next slide)
  - Possible performance specifications
    - Mean response time is less than 1 s when no more than 5000 requests arrive per second
    - 95% of the requests are completed within 1s when no more than 5000 requests arrive / s
      - Note: Workload characteristics are also part of the performance specification

Response time of a system

Request arrives at time t1



Request completes and leaves at time t2

Response time = t2 - t1.
Measured in seconds. Can be expressed as mean, standard deviation, probability distribution etc.

Availability

- Fraction of time the system is up and useable by users
  - Ex: It is common for Internet Service Providers (ISP) to sign Service Level Agreement (SLA) with their commercial customers. One ISP guarantees that its network outage is less than 6 hours per 30 days. The network availability is 1 - 6/(30*24) = 99.17%

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Capacity Planning ➔ Performance analysis

- Capacity planning question:
  - A web server needs to complete an HTTP request within 20ms when there are 500 HTTP requests per second, what CPU speed do you need?
- Let us turn the capacity planning question into a performance analysis question
- Performance analysis question:
  - If the web server has a CPU with *x* MIPS, what is the response time when there are 500 HTTP requests per second?
- If you can solve the performance analysis question for any value of *x*, you can also solve the capacity planning question

Exercise:

- As a capacity planner, your task is to choose the CPU speed (in MIPS) of a web server so that the mean response time to a specific workload is no more than 25ms.
- You talk to a performance analyst about your problem. The analyst knows an algorithm that predicts the mean response time for any CPU speed.
- You take the algorithm and plug in a number of different CPU speeds. The results are recorded below.
- Can you solve your capacity planning problem?

CPU Speed (MIPS)	Predicted mean response time (ms)
2000	40
2500	32
3000	26
3500	22
4000	18

Three performance analysis strategies

- Build the system and perform measurement
- Simulation
- Mathematical modelling

- This course will look at
  - Quantitative methods to determine the QoS metrics of computer systems using
    - Queueing networks
    - Markov chains
  - Using simulation to study performance
  - Optimisation methods such as linear and integer programming

Ex. 1: Server farm power allocation

- A server farm consists of multiple servers
- The servers can run at
  - Higher clock speed with higher power
  - Lower clock speed with lower power
- Ex: Given
  - Higher power = 250W, lower power = 150W
  - Power budget = 3000W
  - You can have
    - 12 servers at highest clock speed
    - 20 servers at lowest clock speed
    - Other combinations
  - Which combination is best?

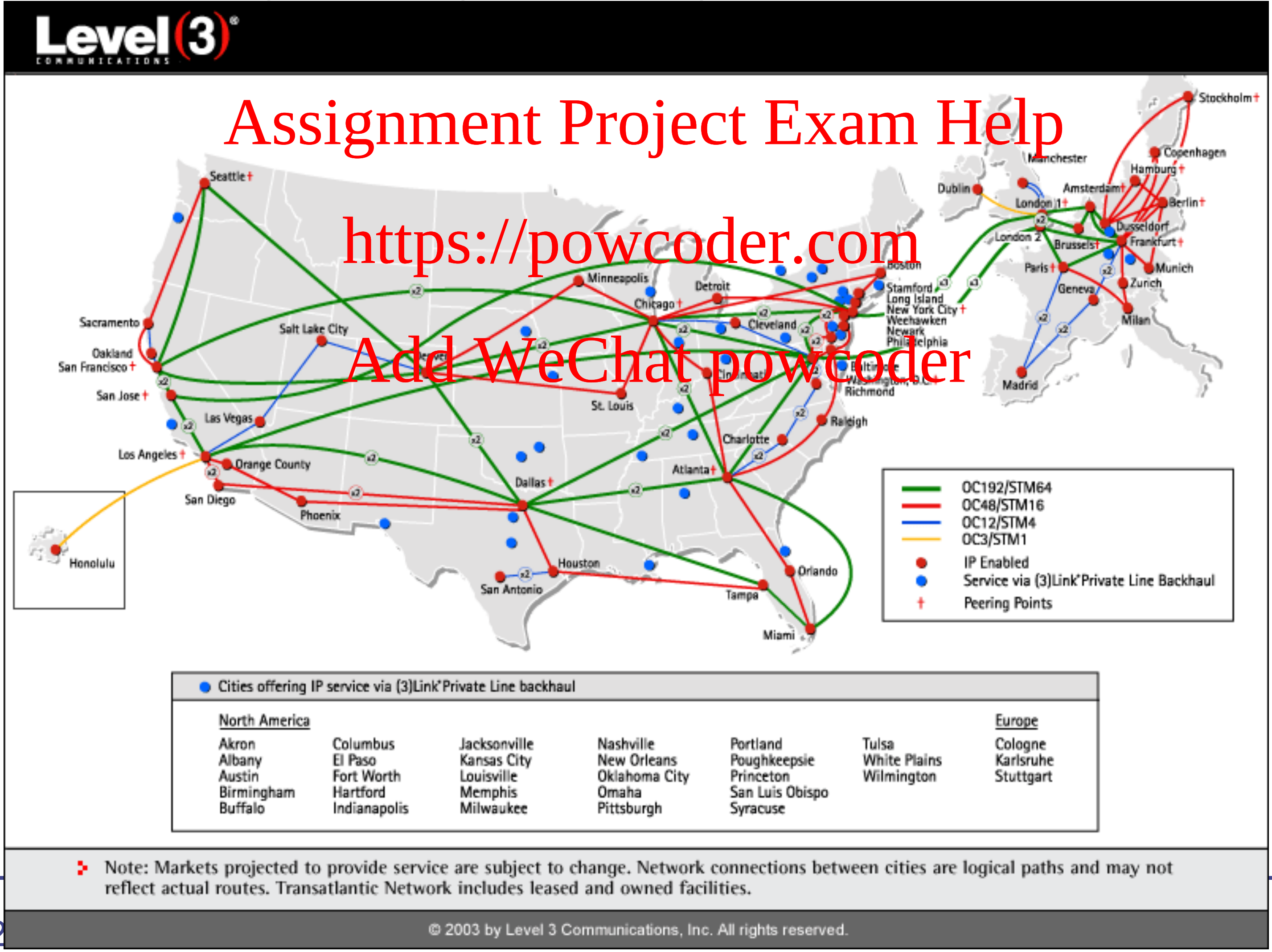
- Queueing theory

Ex 2: Internet data centre availability

- Distributed data centres
- Availability problem:
  - Each data centre may go down
    - Mean time between going down is 90 days
  - Mean repair time is 6 hours
  - Can I maintain 99.9999% availability for 3 out of 4 centres
- Technique: Markov Chain

Ex 3: Network expansion

- You would like to add communication links to a network. The design questions are: Where to add? How much capacity?
- Technique: Integer programming



🟩 OC192/STM64
🟥 OC48/STM16
🟦 OC12/STM4
🟨 OC3/STM1
● IP Enabled
● Service via (3)Link Private Line Backhaul
† Peering Points

● Cities offering IP service via (3)Link Private Line backhaul

North America

Akron
Albany
Austin
Birmingham
Buffalo
Columbus
El Paso
Fort Worth
Hartford
Indianapolis
Jacksonville
Kansas City
Louisville
Memphis
Milwaukee
Nashville
New Orleans
Oklahoma City
Omaha
Pittsburgh
Portland
Poughkeepsie
Princeton
San Luis Obispo
Syracuse
Tulsa
White Plains
Wilmington

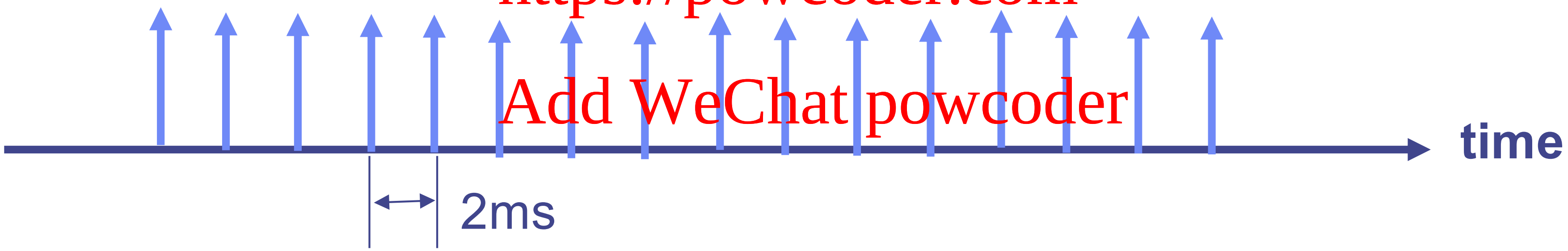
Europe

Cologne
Karlsruhe
Stuttgart

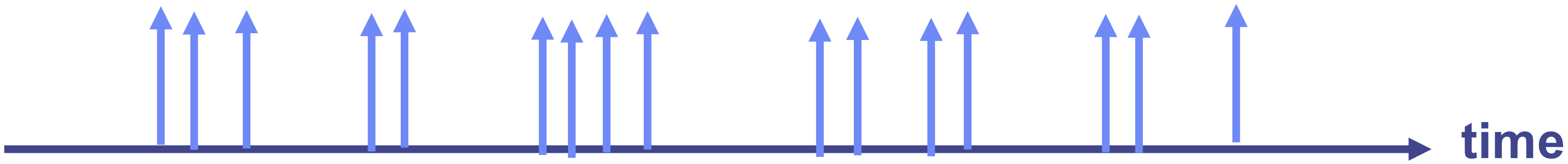
Note: Markets projected to provide service are subject to change. Network connections between cities are logical paths and may not reflect actual routes. Transatlantic Network includes leased and owned facilities.

Why probability?

- The mathematical methods that we are going to study are based on probability theory. Why probability?
- Let us say 500 HTTP requests arrive at the web server in one second
- A deterministic world will mean
  - An HTTP request arrives every 2ms



- But the arrival pattern is not deterministic, it’s random



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QoS metrics

- We have seen 2 QoS metrics
  - Response time
  - Availability
- More QoS metrics
  - Throughput
  - Reliability (Will discuss later in the course)
  - Scalability (Not discussed)

Throughput (1)

- The rate at which requests are completed
- Ex: For network routers, throughput can be measured in
  - Packets per second (pps)
    - Ex: 10 Mpps for 40-byte packets
    - Note: Should specify packet size
  - Mb/s
- Other throughput measures
  - Web site: HTTP requests/s, bytes/s
  - CPU: MIPS, FLOPS

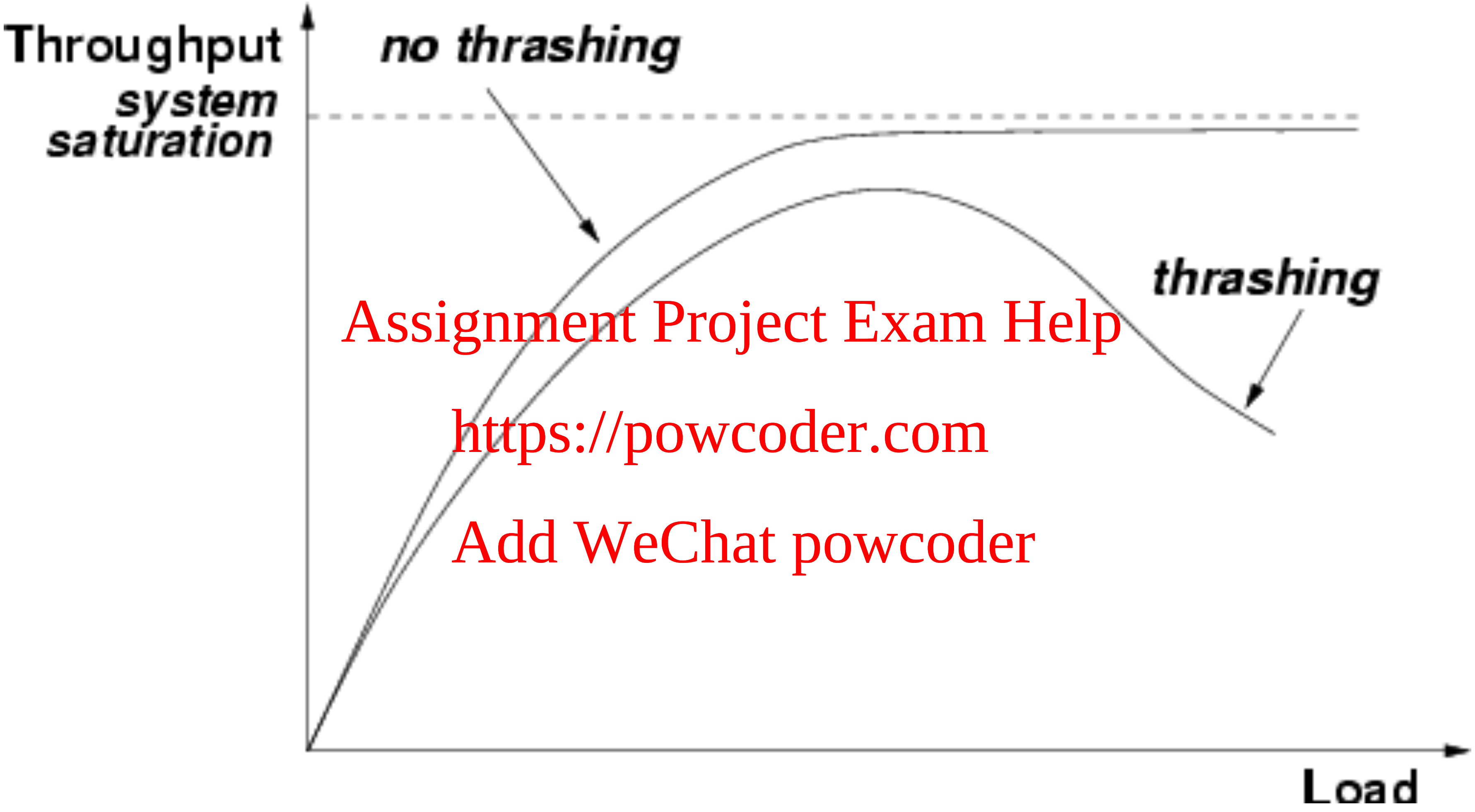
Throughput (2)

- Throughput is a function of the load
  - A disk takes 0.01s to perform an I/O operation
  - Maximum number of I/O operation per s =
  - If 50 I/O operations arrive per second, the throughput = I/O operations/s
  - If 110 I/O operations arrive per second, the throughput = I/O operations
  - Can you find a formula relating throughout, offered load and max capacity?

Throughput (2*)

- If you find it difficult to do the previous page, you can try this real-life analogy.
- Throughput is a function of the load
  - A barister can make a cup of coffee every 30 seconds
  - Maximum number of cups of coffee the barister can make in an hour = [redacted]
  - If 50 customers arrive in an hour and each customer orders a coffee, the barister's throughput = [redacted] coffees / hour
  - If 150 customers arrive in an hour and each customer orders a coffee, the barister's throughput = [redacted] coffees / hour

Throughput (3)



Thrasing = congestion collapse

Throughput (4)

- Performance evaluation can be used to determine the maximum throughput of computer systems
  - Example: bottleneck analysis
    - Topic for next week

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Quantitative performance analysis (3)

- Sample performance analysis question:
  - If the web server has a CPU with *x* MIPS, what is the response time when there are 500 HTTP requests per second?

- Performance analysis question:
  - Given:
    - A computer system with a certain capacity
    - The workload
  - Find
    - The performance (response time, throughput etc) of the system

- Our method is:
  - Build analytical models of computer systems

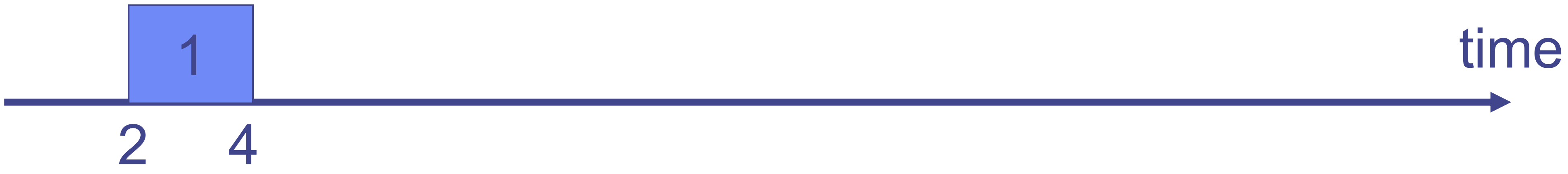
- An important part of the analytical model is “queue”
  - You can surely relate “queues” to “waiting time”

Single server FIFO queue

- Queueing Theory terminologies
  - Server: Processing unit
  - FIFO: First-in first-out
  - Work conserving server
    - The server cannot be idle when there are jobs waiting to be processed in the queue
- Ex: Shop with only one checkout counter
- The server is a resource
  - Queues result from resource contention
- Main concern: response time

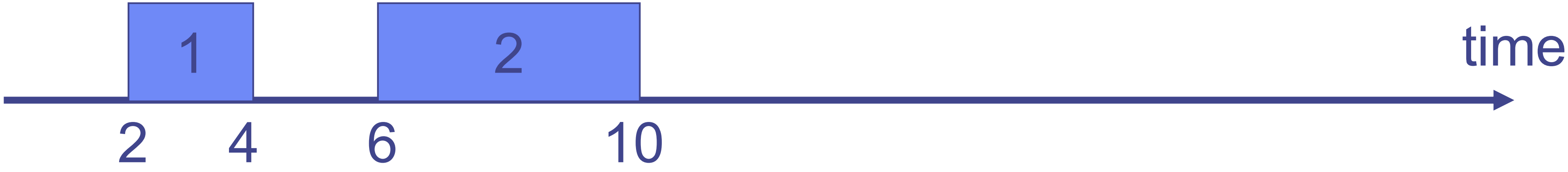
Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3

Assumption: server is idle when job #1 arrives



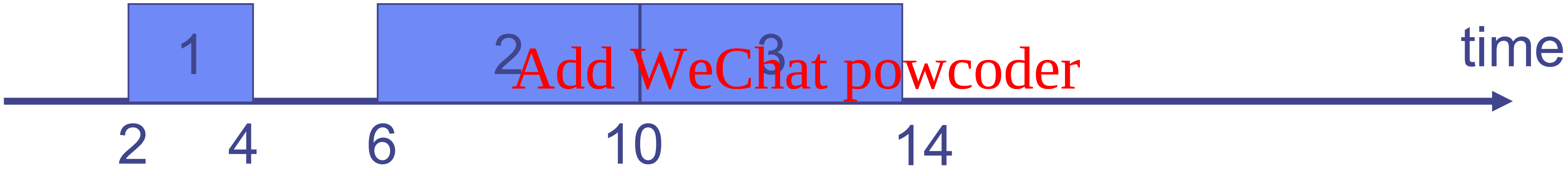
Job #1 is admitted into the server immediately since the server is idle.
Job #1 is completed and leaves the system at time 4.

Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3



Job #2 arrives when the server is idle. It gets admitted immediately.
Job #2 will be completed at time 10.

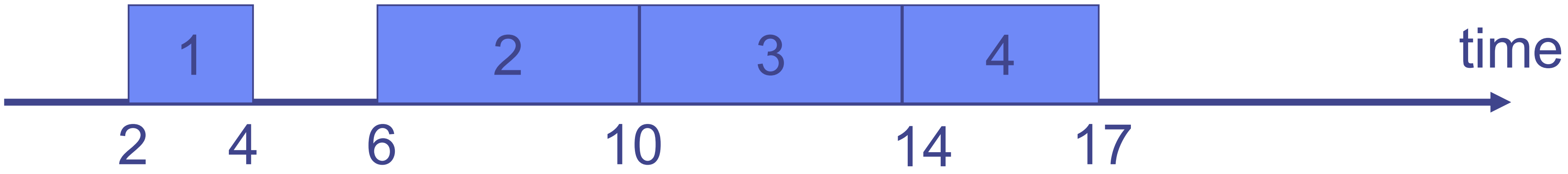
Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3



Job #3 arrives when Job #2 is being served i.e. the server is busy. Job #3 has to wait in the queue.

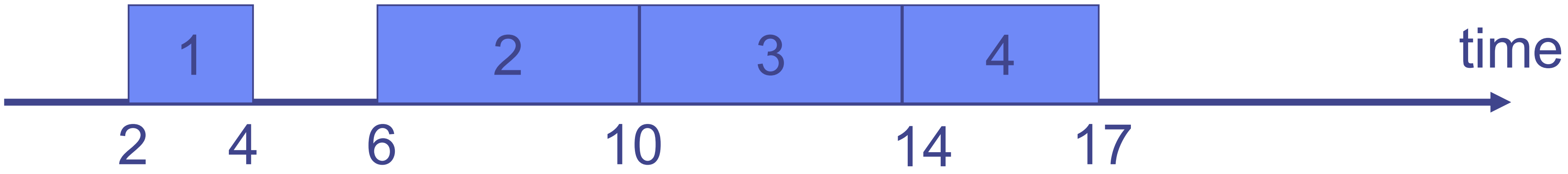
Server starts processing Job #3 immediately after finishing Job #2.

Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3



Job #4 arrives when the server is processing Job#2 and Job#3 is in the queue. Job #4 joins the queue. It gets served at time 14, immediately after Job#3 is completed.

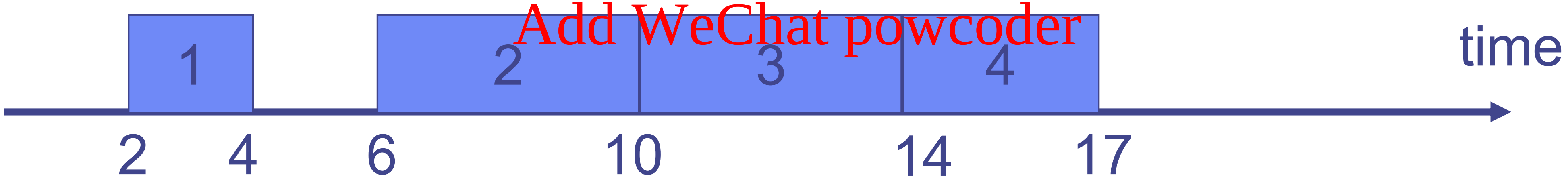
Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3



- Definition: Response time = Departure time - arrival time

  Ex: Response time for Job#4 = 17 – 9 = 8 (= 5 + 3)
- Response time = Waiting time + Processing time

Job index	Arrival time	Processing time required
1	2	2
2	6	4
3	8	4
4	9	3



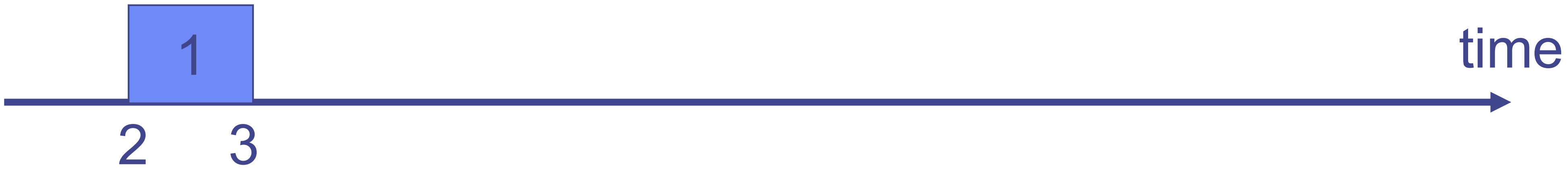
- Definition: Utilisation = Percentage of time over which the server is busy
- What is the utilisation of the server over the first 12s?
  - 8/12 = 66.7%

Single server FIFO queues

- Can be used to model
  - Shop with only one checkout counter
  - A single processor processing jobs in FIFO order
  - A disk processing job in FIFO order
- Model
  - An abstraction of the real system
  - Need to capture enough details to meet our analysis requirements

What if both inter-arrival time and processing time are determinisitic?

Job index	Arrival time	Processing time required
1	2	1
2	4	1
3	6	1
4	8	1



What is the waiting time for each job?
What is the response time for each job?

Determining response time

- Generally we need to know
  - The arrival pattern
    - Ex: The arrival rate
    - Ex: The inter-arrival time probability distribution
  - The service time probability distribution
    - The time required to process the job
- Since we are interested in response time, our models capture the time related aspects of the real systems e.g. queueing, processing units
- We will learn different methods to determine response time in this course

Service time

- Time require to process a request at a resource
  - Ex: The service time to send a 1000 byte packet over a 10 kbps link is 0.8s. In this case,
    - Service time = packet size / transmission rate
  - Ex: The service time to fetch a X byte large file from a disk is
    - Seek time + X / transfer rate
  - For a class of resources, we have
    - Service time = Overhead + Job size / Processing rate

Summary

- What capacity planning is

- Very important: A capacity planning problem can be solved by solving a series of performance analysis problems

- Performance metrics
  - Response time, waiting time, throughput

- Modelling of single server queues

References

- Reading:
  - Menasce et al, Chapters 1 & 2
  - OR
  - Harcol-Balter. Chapters 1 & 2.
- Exercises:
  - Revision problems:
    - See course website
  - You are expected to try these exercises. Solutions will be available on the web.