Design and Engineering of Computer Systems

Lecture 31: Performance measurement

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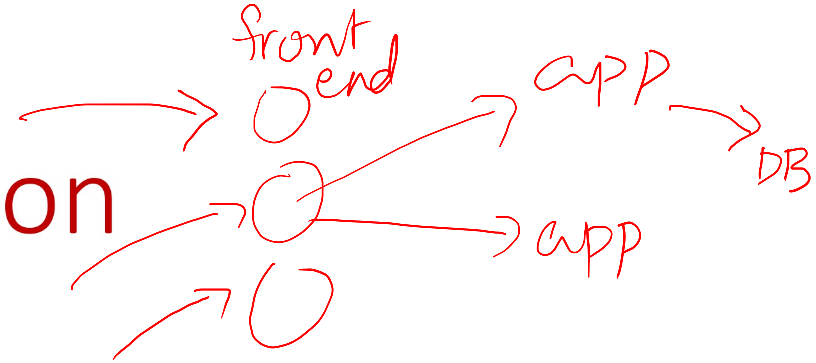
Performance engineering

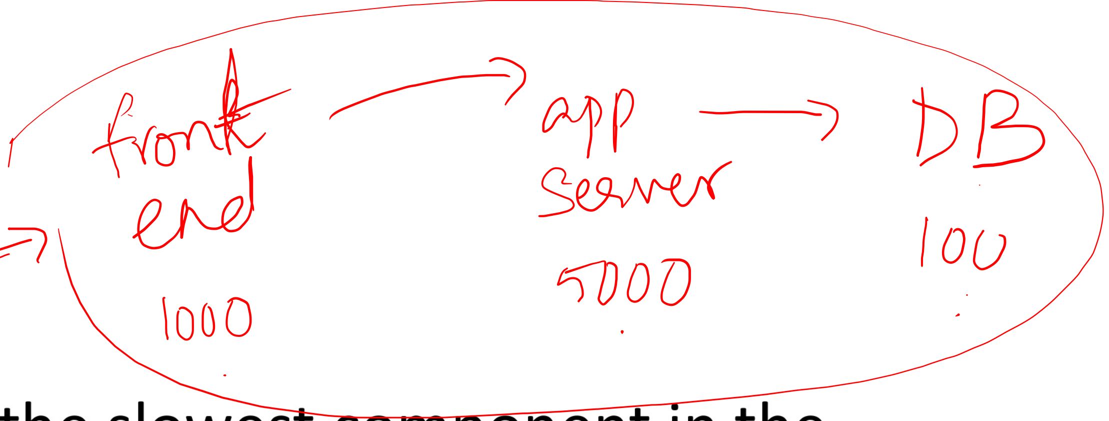
- So far in the course: how computer systems are developed
- This week: performance engineering
  - Measuring and optimizing performance of computer systems
  - How is performance measured? What to measure, how to measure, what are parameters we can change, what output metrics should we observe, ..
  - Performance analysis: simple back-of-the-envelope calculations to make sense of the performance measurements
  - Identify performance bottlenecks, which component is slow, and why
  - Techniques to optimize performance: within a single machine and across the entire system

Example: multi-tier web application



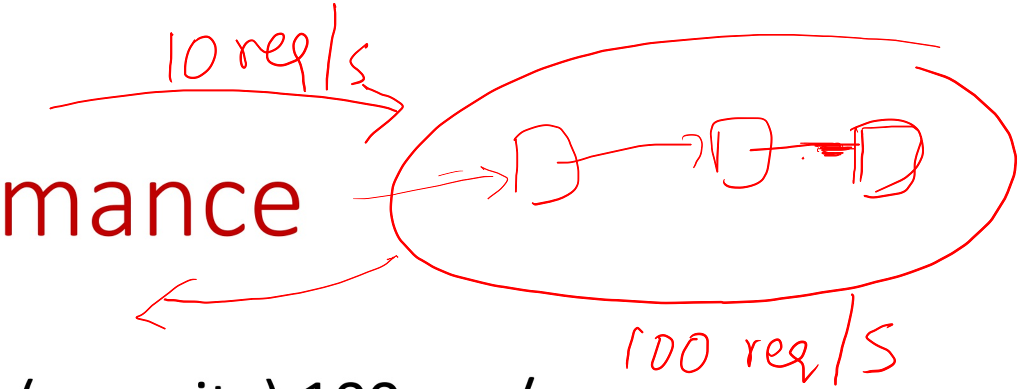
- Consider a multi-tier application (many examples seen so far)
  - Front-end web servers, multiple application servers, backend databases
  - Clients make requests, processed by system, responses sent back
- Incoming traffic into the system can be measured using: load ?
  - Number of concurrent clients connected to the system
  - Incoming rate of requests per second
  - Mix of various types of requests in the incoming traffic
- Performance of the system measured by (average values of):
  - Throughput: number of requests per second handled successfully
  - Response time / RTT / latency / delay: time taken by the system to return back a response to a client request (varies by type of request)

Performance bottleneck

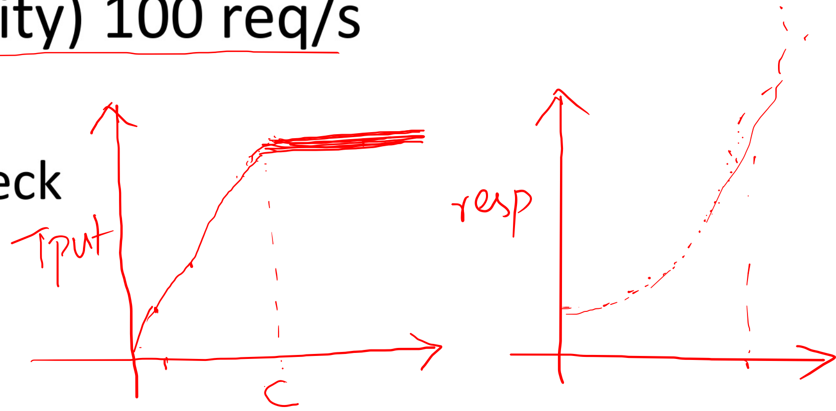


- The performance of a system is limited by the slowest component in the system (bottleneck)
- Consider a web application servicing one type of requests
  - Front-end can serve 1000 req/s, app server can handle 5000 req/s, backend database can process 100 req/s
  - Max throughput of the system is 100 req/s (capacity)
  - Database component will be the performance bottleneck and will be fully occupied at peak input load (other components will not be as busy)
  - Database component takes approx. 1/100 seconds = 10 milliseconds to process each request (service demand)
  - Response time of system will be at least 10 millisecond + time needed at other components
- Sometimes, the network can also be a bottleneck, not any component
  - Some switch on path between clients and server can only forward 50 req/s

Understanding system performance

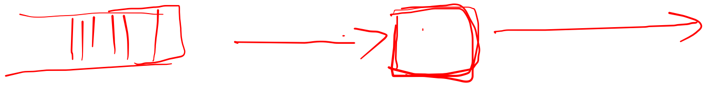


- Consider web application with max throughput (capacity) 100 req/s
- Suppose incoming traffic into system is only 10 req/s
  - The system throughput is 10 req/s, no performance bottleneck
  - No component overwhelmed, quick (low) response time
- As incoming load approaches capacity, e.g., 90 req/s
  - All incoming requests are served, throughput is 90 req/s
  - Bottleneck component starts to get busy, queue builds up, responses take longer
- If incoming load exceeds system capacity
  - Bottleneck component fully saturated, max throughput (capacity) achieved, throughput flattens (cannot increase any more)
  - Response times are higher due to queueing delays, continue to increase with increasing load

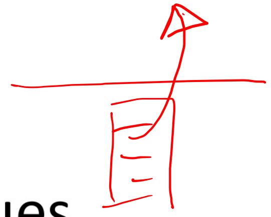


Understanding overload

- What happens when incoming load to server greatly exceeds capacity?
  - Throughput flattens, cannot increase beyond bottleneck capacity
  - Response times keep increasing as requests get queued up at bottleneck (high queueing delay)

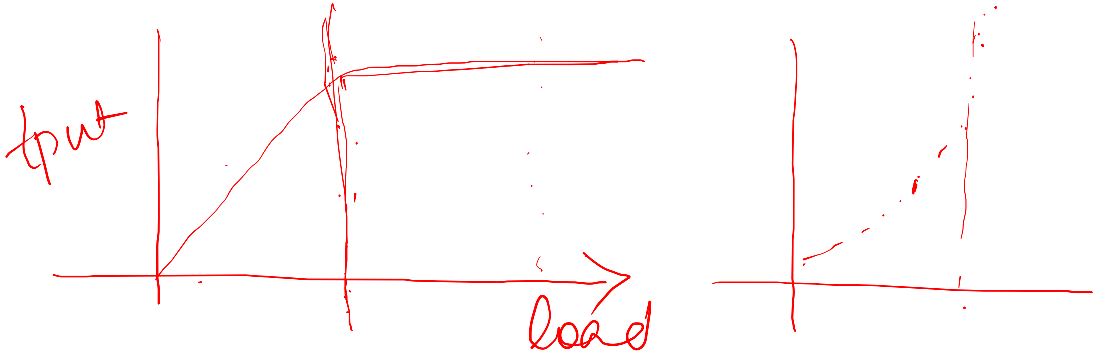


  - App software cannot process requests, returns error messages (e.g., HTTP server returns code of "503 service unavailable" if it is overloaded)
  - TCP sender does not get acks, terminates connection (socket syscalls fail)
  - Networking routers/switches/NIC may get overloaded, packets fill up queues inside router or device driver, packet are dropped

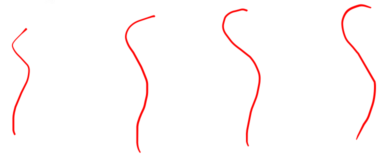


- Result of overload: very high response time (for requests that complete) or errors (requests get no response at all, or get error messages)

Understanding saturation

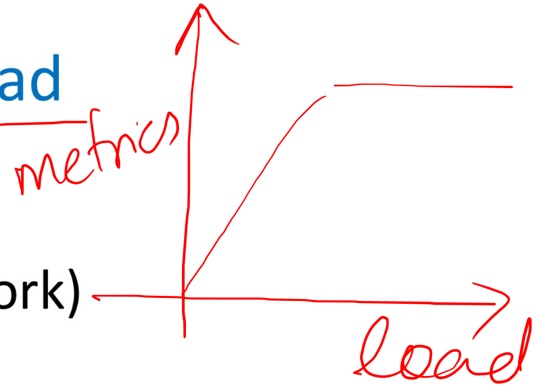


- Ideal operating point of a system: just below max capacity or saturation
  - Close to max throughput, not too long response times, no errors
- At saturation, some hardware resource at bottleneck is fully (100%) utilized
  - E.g., all CPU cores are fully busy with no spare CPU cycles
  - E.g., hard disk is running at full capacity performing reads/writes
- How to improve capacity?
  - Increase hardware resources at bottleneck component
  - Or, optimize system to use hardware resources more efficiently
- Sometimes, bottleneck due to software issues only (no hardware resource is fully utilized)
  - E.g., maximum number of file descriptors opened by process, cannot open any more
  - E.g., threads wasting time waiting for locks, even though CPU is free
  - Such issues can be fixed by rewriting code or tuning OS parameters



Performance: parameters and metrics

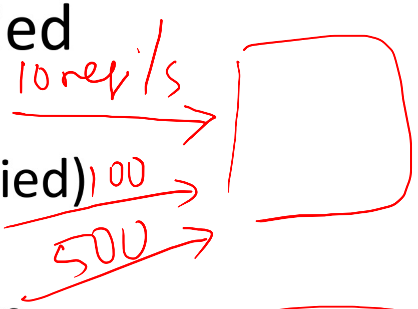
- Given a computer system (with certain capacity and configuration of various components), how to measure its performance?
- Input parameters on which performance depends / incoming load
  - Number of concurrent users/requests in the system
  - Rate (requests/sec) of incoming traffic
  - Mix of various types of requests (which require different amounts of work)



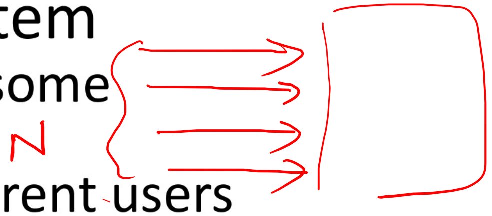
- Performance metrics / outputs measured
  - Throughput of the system (averaged over a time window, end-to-end and per-hop)
  - Response time or latency (averaged, end-to-end and per-hop)
  - Utilization of various resources at components, especially bottleneck (averaged)
  - Various kinds of errors and failures (counts)
- Load testing of a system: vary incoming load, measure performance

Types of load testing

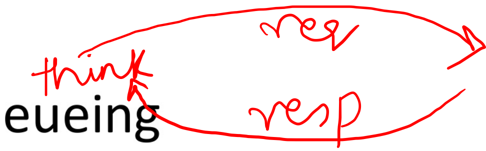
- Different types of load tests based on which input parameter is varied
- Open loop load testing: vary rate of incoming traffic into system
  - Generate N req/s for increasing values of N (mix of requests can also be varied)
  - Can be implemented by firing a request every 1/N second



- Closed loop load testing: vary number of concurrent users of system
  - N concurrent users, each user sends a request, gets response, waits for some amount of time ("think time"), sends next request
  - Can be implemented by having N threads/processes emulating N concurrent users

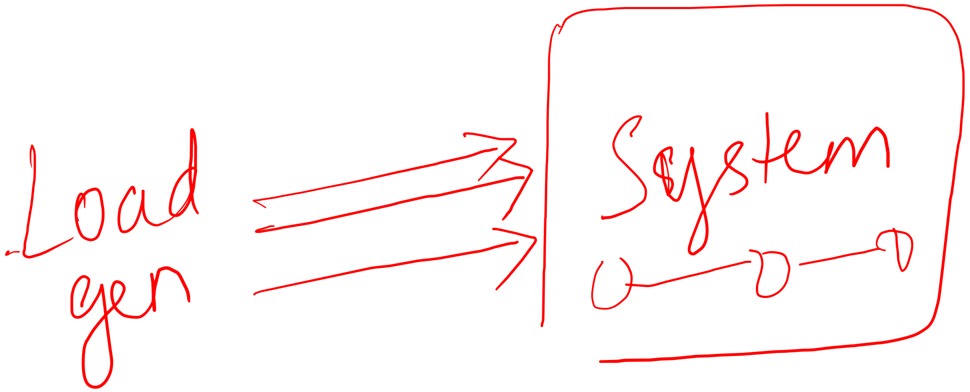


- Both techniques are valid ways of varying input load of system
  - Open loop testing can lead to higher number of concurrent users, more queueing



- Load generators: software programs or hardware appliances that generate load to test a computer system in open/closed loop manner
  - Provide knobs to vary rate of requests, or number of concurrent users etc.

Running a load test



- How to run a load test
  - Setup load generator, system under test and connect them suitably
  - Generate increasing amounts of load from load generator to system (by varying rate of incoming traffic or number of concurrent requests)
  - Measure output metrics (throughput, response time, errors, utilizations) for each value of input load
  - Eliminate sources of non-determinism (e.g., pin threads to CPU cores)
  - Ensure load generator or connecting network is not the bottleneck
- Results of load test: performance metrics vs. incoming load
- What after load test? Performance analysis and engineering
  - Analyze and understand performance metrics, identify bottleneck
  - Optimize system, repeat load test
  - Stop when system performance meets the expected incoming load

Summary

- In this lecture:
  - What is performance: input parameters, output metrics
  - How to measure performance
- Programming exercise. Setup a simple web server using the freely available Apache server. Apache JMeter is a load generator to test web servers. Try to run a simple load test using JMeter.