Design and Engineering of Computer Systems

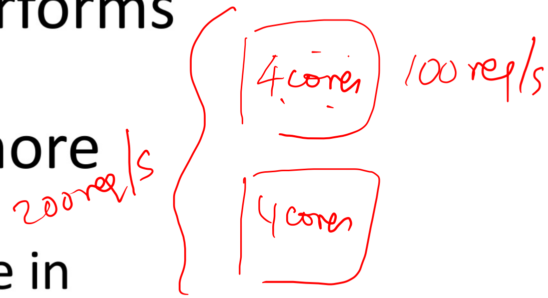
Lecture 35: Performance Scalability

Mythili Vutukuru

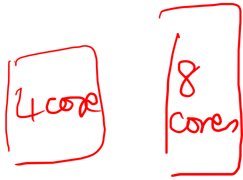
IIT Bombay

Performance scalability

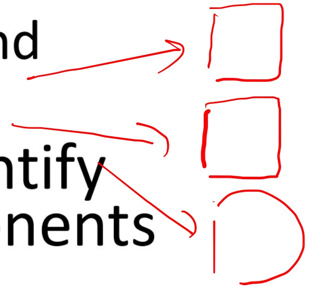
- Performance measurement and analysis so far: how a system performs with a given configuration (CPU cores, memory, …)
- Performance scalability: how performance improves if we give more resources to the system
  - A system with good performance scalability will improve its performance in proportion to the increase in resources



- After we have optimized performance of a system to the best possible extent, only way to improve performance further is by scaling:
  - Vertical scaling / scale-up: add more hardware resources (e.g., CPU cores / memory / whichever resource is bottleneck) to existing machine
  - Horizontal scaling / scale-out: add more replicas of bottleneck component and distribute load between replicas

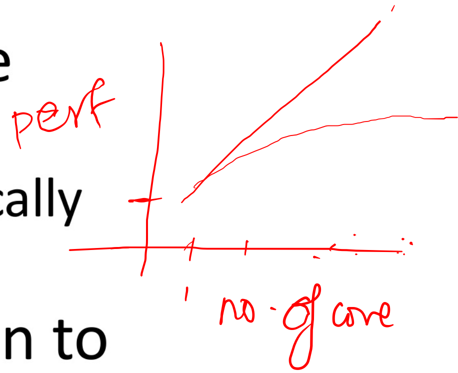


- Cloud management systems provide auto-scaling: automatically identify when incoming load is beyond capacity, and scale bottleneck components



Multicore scalability

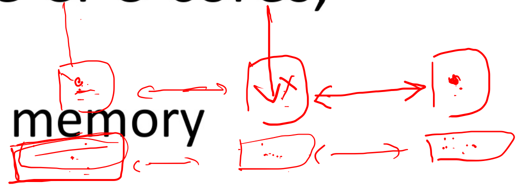
- One way to do vertical scaling for systems where CPU is performance bottleneck is to add more CPU cores to system
  - Cloud orchestration systems monitor CPU usage of components and dynamically assign more/less CPU cores based on utilization
- Multicore scalability: application performance increases in proportion to CPU cores assigned to application
- Applications that can be parallelized easily have good multicore scalability
- Common reasons for poor multicore scalability
  - Cache coherence overheads due to accessing shared memory via multiple CPU cores with private caches
  - Locking at application and OS serializes access to critical sections, reduces parallelism in application

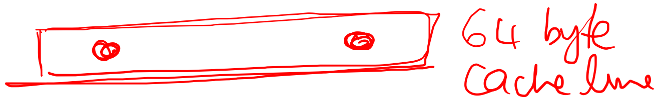


Cache coherence overhead

```
bool isLocked = false
void acquire_lock() {
   while(test-and-set(isLocked, true) == true);
}
```

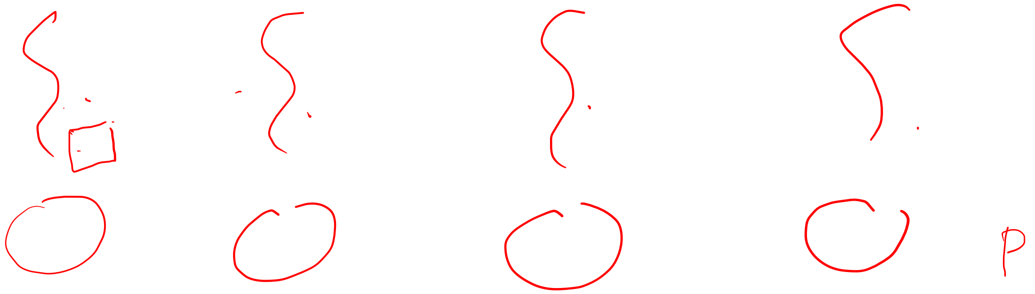
- When same memory location / variable is accessed from multiple CPU cores, multiple copies of cached data need to be kept in sync
  - Snooping or directory to keep track of which CPU core has cached which memory addresses
  - When one CPU core updates its private cache, other cores must update or invalidate their cached copy
  - Not just with true sharing, but also due to false sharing (CPU cores access different memory addresses located on same 64 byte cache line)





- Why do CPU cores access same memory location?
  - Multiple threads of process access same parts of memory image from different cores
  - Multiple processes in kernel mode can access same OS code/data from different cores
  - Variables like locks are accessed from multiple cores, resulting in cache line with lock variable bouncing across CPU cores during lock acquisition

Multicore speedup



- Perfect multicore scalability possible only if all threads/processes can execute independently in parallel on multiple CPU cores
- Sometimes, threads cannot execute in parallel, and must execute serially for some time, leading to poor multicore scalability
  - Example: only one thread at a time can execute critical section
  - Example: one thread in pipeline waits for previous thread to finish
- Amdahl's law: estimate performance gains due to parallelism
  - Let T1 = time required to perform a task on one CPU core
  - Let Tp = time required to perform task when running in parallel on "p" cores
  - Let α = fraction of task that can be parallelized
  - We have Tp = (α * T1 / p) + (1- α) * T1
  - Speedup due to using multiple cores = T1/Tp (ideally p if α=1)
  - For large values of p, speedup approx. 1/(1- α)
  - If α is small, speedup is small, poor multicore scalability

$$\frac{T_1}{T_p} = p$$

$$T_p = \frac{\alpha \cdot T_1}{p} + (1-\alpha)T_1$$

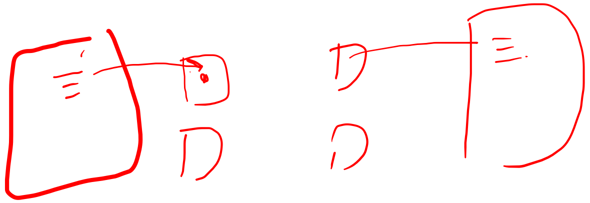
$$\frac{T_1}{T_p} \approx \frac{1}{\frac{\alpha}{p} + (1-\alpha)} \approx \frac{1}{1-\alpha}$$

Techniques to improve multicore scalability

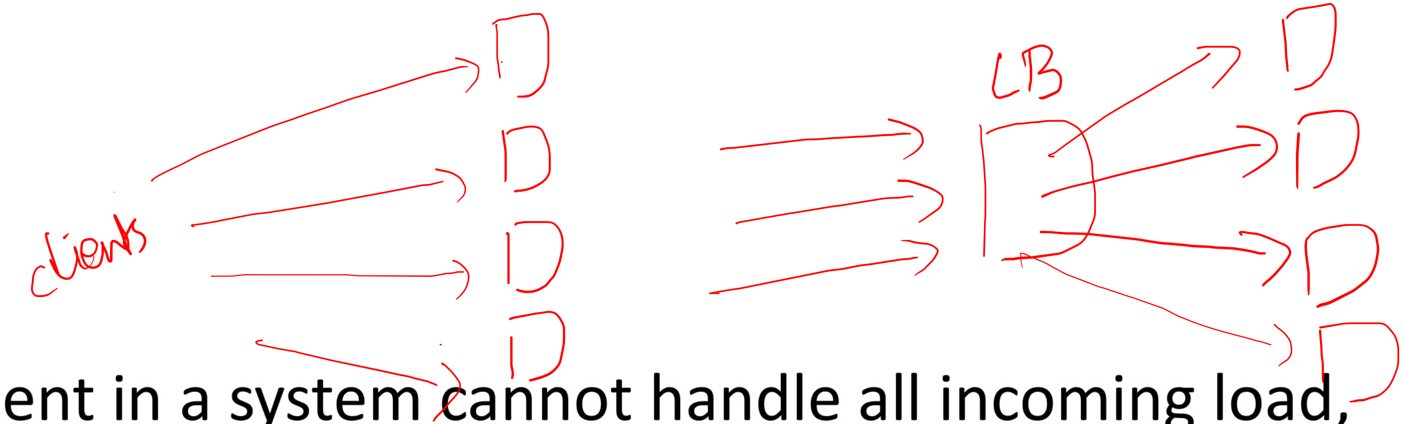
- Avoid sharing data across cores as far as possible: split application data into per-core / per-thread slices where possible
  - Split across cores at granularity of cache lines to avoid false sharing

- Use locks only when required, as locks cause cache coherence traffic and also serialize code execution
  - Modern lock implementations avoid excess cache coherence overheads when multiple threads on different cores contending for lock
- Lock-free application design, lock-free data structures

- OS designs evolving to scale well with multiple CPU cores, by splitting OS data structures into per-core slices where possible
- Modern OS have NUMA awareness: in NUMA systems (some CPU cores closer to some main memory), run process on CPU cores close to memory image

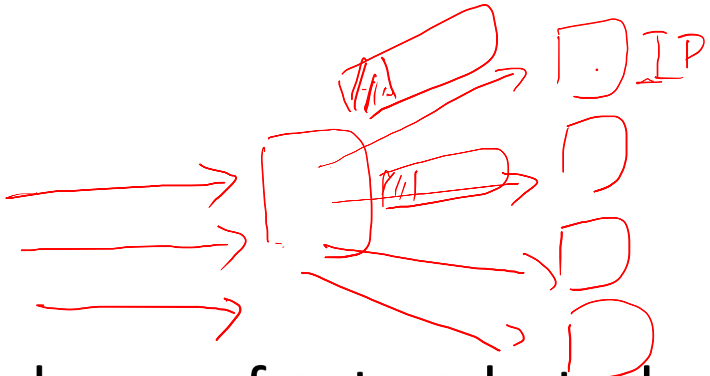


Horizontal scaling

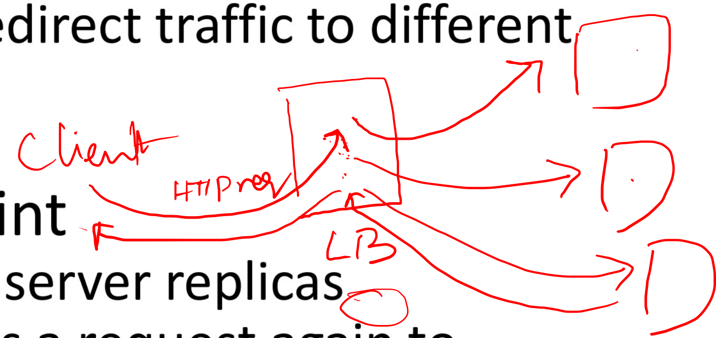


- Suppose bottleneck component in a system cannot handle all incoming load, no matter how many optimizations are performed. What next?
- Horizontal scaling: instantiate multiple replicas of bottleneck component, distribute incoming load amongst replicas
  - Automatically done by cloud orchestration systems
- How do other components / clients contact multiple replicas?
  - Other components are told of multiple replicas explicitly (e.g., HTTP clients learn of multiple server replica IP addresses via DNS)
  - Or, all incoming traffic comes to a load balancer, which redirects traffic to replicas
  - Load balancer based design more popular as scaling is transparent to others
- Load balancers are special software/hardware components which redirect traffic to replicas as per some policy
  - Need to perform well to handle all incoming load without becoming bottleneck
  - Must adapt dynamically to changing load and changing number of replicas

Load balancer design

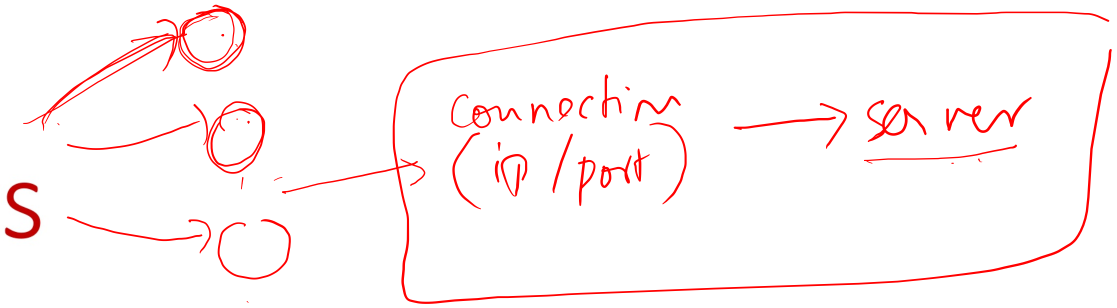


- Load balancer can operate at many layers of network stack
- Network layer load balancer: only changes dst IP/port to redirect packets
  - All packets arrive to one (virtual) IP address/port number of server
  - Load balancer rewrites destination IP address/port number to redirect traffic to different server replicas
  - Does not perform any transport/application layer processing

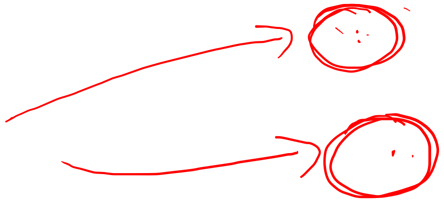


- Application layer load balancer: acts as application endpoint
  - Clients and other components connect to load balancer and not server replicas
  - Load balancer receives app requests (e.g., HTTP requests), makes a request again to server replica, fetches response, and sends it back to clients
- Application layer HTTP load balancers also serve other HTTP functions
  - Directly serve static content without contacting server replicas
  - Caching of responses from replicas, SSL termination, …
  - Called reverse proxy servers (to differentiate from proxy servers at client side)

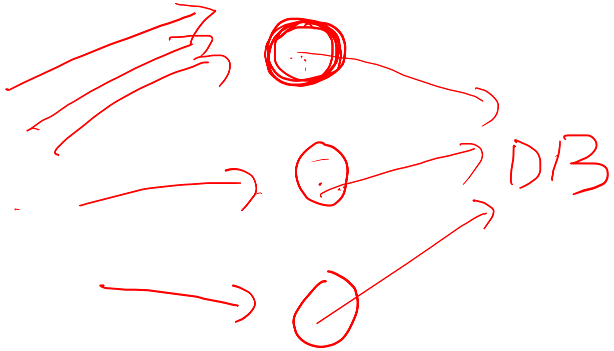
Load balancer policies



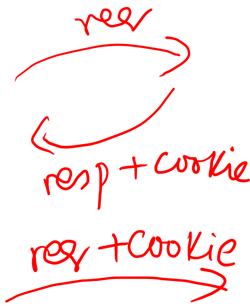
- How does load balancer distribute traffic to different replicas?
  - Note that traffic of one TCP/UDP connection should always go to same replica
- Round robin: assign connections to replicas in round robin manner
  - If first packet of a connection, pick one of the servers in round robin manner, store mapping from connection identifier (src/dst IP/port) to assigned server in a table
  - If packet of ongoing connection, redirect packet to previously assigned server
- Hashing: use hash of connection identifier to pick one of the server replicas
  - E.g., hash(src port, dst port, src IP, dst IP) modulo N, where N is number of servers
  - Problem: mappings of existing connections change when N changes, handle such changes carefully to not disrupt ongoing connections
- Other policies possible, e.g., pick least loaded server for a new connection
- What if requests of one user, coming on different connections, sent to different replicas? How is user state maintained correctly across replicas?



User stickiness in load balancing

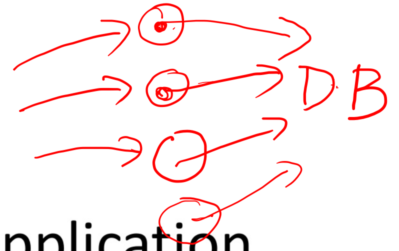


- Some applications want to ensure "stickiness" of users or "sessions"
  - When user is purchasing product from e-commerce site, transaction happens over multiple TCP connections, which can go to different replicas
  - We would like all TCP connections of a user in one "session" to go to same replica
- Why stickiness? All data related to user's session (e.g., shopping cart) is available in the same replica, instead of fetching from remote database frequently
  - Otherwise, every replica has to store/fetch session state in remote database often
- First connection of a session assigned to any replica using existing policy, e.g., round robin. Mapping from session to server stored. All subsequent connections of session assigned to same replica
- How is a user session identified? User source IP address, or HTTP cookies (special data in HTTP requests to identify users), ….
- With user stickiness, user data can be stored locally within components for faster access, need not store/fetch data in remote database servers for every request

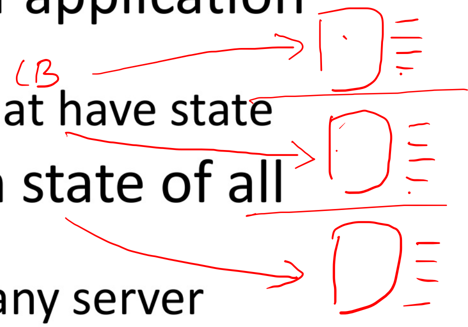


Managing application state across replicas

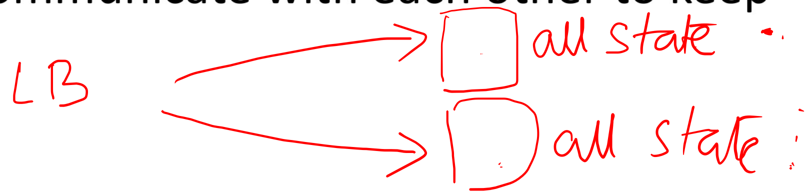
- Application components store user state, e.g., current contents of user's shopping cart. How to manage such state across multiple server replicas?
- Stateless design: front end and app servers store no state, all state is stored/retrieved from backend databases for each request. Backend common to all replicas
  - High overhead due to remote access needed for every request
  - Easy to add server replicas and scale system horizontally; simple load balancer design
  - User level stickiness not needed, any replica can handle any user session



- Shared nothing stateful design: each server replica locally stores a slice of application state for some users/sessions. User state is partitioned across replicas
  - Load balancer should ensure user level stickiness, redirect user traffic to replicas that have state



- Fully replicated stateful design: all server replicas locally store application state of all users/sessions
  - Load balancer need not ensure user stickiness; any connection can be assigned to any server
  - Higher overhead than shared nothing design; servers must communicate with each other to keep all copies of user state consistent



Summary

- In this lecture:
    - Performance vs. scalability
    - Vertical scaling and multicore scalability
    - Horizontal scaling and load balancing
- Measure performance of any simple application/web server with increasing CPU cores. See if you get multicore scalability.