CSE 451: Operating Systems
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Module 23
Distributed Systems

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What is a "distributed system"?

- Nearly all systems today are distributed in some way
  - they use email
  - they access files over a network
  - they access printers over a network
  - they're backed up over a network
  - they share other physical or logical resources
  - they cooperate with other people on other machines
  - they access the web
  - they receive video, audio, etc.

Distributed systems are now a requirement

- Economics dictate that we buy small computers
- Everyone needs to communicate
- We need to share physical devices (printers) as well as information (files, etc.)
- Many applications are by their nature distributed (bank teller machines, airline reservations, ticket purchasing)
- To solve large problems, we need to get large collections of small machines to cooperate together (e.g., Google's search infrastructure, BOINC (SETI@home))

Loosely-coupled systems

- Earliest systems used simple explicit network programs
  - FTP (rcp): file transfer program
  - telnet (rlogin/rsh): remote login program
  - mail (SMTP)
- Each system was a completely autonomous independent system, connected to others on the network

- Even today, most distributed systems are loosely-coupled
  - each CPU runs an independent autonomous OS
  - computers don't really trust each other
  - some resources are shared, but most are not
  - the system may look differently from different hosts
  - typically, communication times are relatively long

Closely-coupled systems

- A distributed system becomes more "closely-coupled" as it
  - appears more uniform in nature
  - runs a "single" operating system
  - has a single security domain
  - shares all logical resources (e.g., files)
  - shares all physical resources (CPUs, memory, disks, printers, etc.)
- In the limit, a distributed system looks to the user as if it were a centralized timesharing system, except that it's constructed out of a distributed collection of hardware and software components

Tightly-coupled systems

- A “tightly-coupled” system usually refers to a multiprocessor
  - runs a single copy of the OS with a single job queue
  - has a single address space
  - usually has a single bus or backplane to which all processors and memories are connected
  - has very low communication latency
  - processors communicate through shared memory

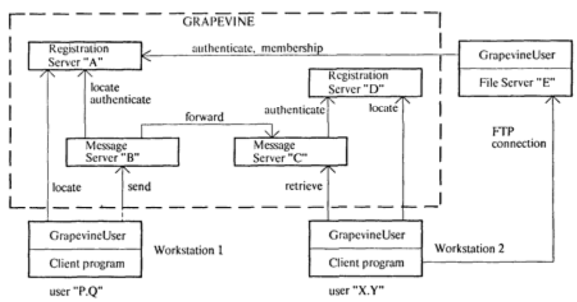
Some issues in distributed systems

- Transparency (how visible is the distribution)
- Security
- Reliability
- Performance
- Scalability
- Programming models
- Communication models

Example: Grapevine distributed mail service

- Xerox PARC, 1980
  - cf. Microsoft Outlook/Exchange today!!!!!
- Goals
  - cannot rely on integrity of client
  - once the system accepts mail, it will be delivered
  - no single Grapevine computer failure will make the system unavailable to any client either for sending or for receiving mail
- Components
  - GrapevineUser package on each client workstation
  - Registration Servers
  - Message Servers
- Implementation: Remote Procedure Call

Grapevine: Functional diagram



Grapevine: Sending a message

- User prepares message using mail client
- Mail client contacts GrapevineUser package on same workstation to actually send message
- GrapevineUser package
  - contacts any Registration Server to get a list of Message Servers
  - contacts any Message Server to transmit message
    - presents source and destination userids, and source password, for authentication
      - Message Server uses any Registration Server to authenticate
    - sends message body to Message Server
      - Message Server places it in stable storage and acknowledges receipt

Grapevine: Transport and buffering

- For each recipient of the message, Message Server contacts any Registration Server to obtain list of Message Servers holding mail for that recipient
- Sends a copy of the message to one of those Message Servers for that recipient

Grapevine: Retrieving mail

- User uses mail client to contact GrapevineUser package on same workstation to retrieve mail
- GrapevineUser package
  - contacts any Registration Server to get a list of each Message Server holding mail for the user ("inbox site")
  - contacts each of these Message Servers to retrieve mail
    - presents user credentials
      - Message Server uses any Registration Server to authenticate
    - acknowledges receipt of messages so that the server can delete them from its storage

Grapevine: Scalability

- Can add more Registration Servers
- Can add more Message Servers
- Only thing that didn't scale was handling of distribution lists
  - the accepting Message Server was responsible for expanding the list (recursively if necessary) and delivering to an appropriate Message Server for each recipient
  - some distribution lists contained essentially the entire user community
- Jeff Dean (Google) told us they don't even think about more than two decimal orders of magnitude
  - fundamental design decisions will need to change
  - advances in technology will make it possible

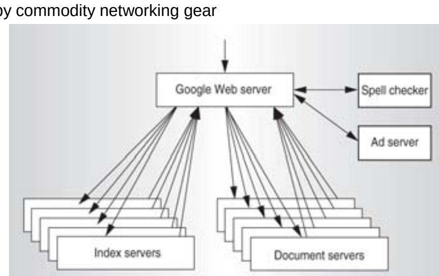
Example: Google search infrastructure

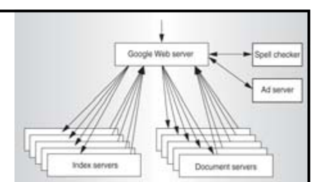
- It's likely that Google has several million machines
  - But let's be conservative – 1,000,000 machines
  - A rack holds 176 CPUs (88 1U dual-processor boards), so that's about 6,000 racks
  - A rack requires about 50 square feet (given datacenter cooling capabilities), so that's about 300,000 square feet of machine room space (more than 6 football fields of real estate – although of course Google divides its machines among dozens of datacenters all over the world)
  - A rack requires about 10kw to power, and about the same to cool, so that's about 120,000 kw of power, or nearly 100,000,000 kwh per month ($10 million at $0.10/kwh)
    - Equivalent to about 20% of Seattle City Light's generating capacity

- There are multiple clusters (of thousands of computers each) all over the world
- *Many hundreds of machines are involved in a* <u>*single*</u> *Google search request* (remember, the web is 400+TB)

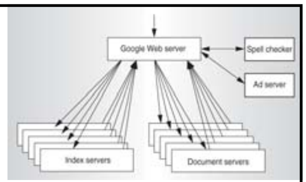
1. DNS routes your search request to a nearby cluster

- A cluster consists of Google Web Servers, Index Servers, Doc Servers, and various other servers (ads, spell checking, etc.)
  - These are cheap standalone computers, rack-mounted, connected by commodity networking gear



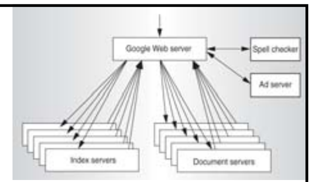


2. Within the cluster, load-balancing routes your search to a lightly-loaded Google Web Server (GWS), which will coordinate the search and response



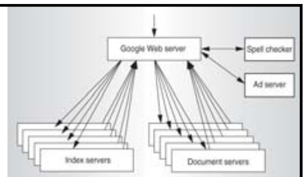
- The index is partitioned into "shards." Each shard indexes a subset of the docs (web pages). Each shard is replicated, and can be searched by multiple computers – "index servers"

3. The GWS routes your search to one index server associated with each shard, through another load-balancer
4. When the dust has settled, the result is an ID for every doc satisfying your search, rank-ordered by relevance



- The docs, too, are partitioned into "shards" – the partitioning is a hash on the doc ID. Each shard contains the full text of a subset of the docs. Each shard can be searched by multiple computers – "doc servers"

5. The GWS sends appropriate doc IDs to one doc server associated with each relevant shard
6. When the dust has settled, the result is a URL, a title, and a summary for every relevant doc



7. Meanwhile, the ad server has done its thing, the spell checker has done its thing, etc.
8. The GWS builds an HTTP response to your search and ships it off

- Many hundreds of computers have enabled you to search 400+TB of web in ~100 ms.

Google: The Big Picture

- Enormous volumes of data
- Extreme parallelism
- The cheapest imaginable components
  - Failures occur all the time
  - You couldn't afford to prevent this in hardware
- Software makes it
  - Fault-Tolerant
  - Highly Available
  - Recoverable
  - Consistent
  - Scalable
  - Predictable
  - Secure

How on earth would you enable mere mortals write hairy applications such as this?

- Recognize that many Google applications have the same structure
  - Apply a "map" operation to each logical record in order to compute a set of intermediate key/value pairs
  - Apply a "reduce" operation to all the values that share the same key in order to combine the derived data appropriately
- Build a runtime library that handles all the details, accepting a couple of customization functions from the user – a Map function and a Reduce function
- That's what MapReduce is
  - Supported by the Google File System and the Chubby lock manager
  - Augmented by the BigTable not-quite-a-database system