Distributed Systems

22. Clusters

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Computer System Design

Highly Available Systems

- Incorporate elements of fault-tolerant design
  - Replication, TMR
- Fully fault tolerant system will offer non-stop availability
  - But you can't achieve this!

Problem:
- ↑ in availability ⇒ ↑ $$

Highly Scalable Systems

- SMP architecture

Problem:

Performance gain as *f*(# processors) is sublinear
- Contention for resources (bus, memory, devices)
- Also … the solution is expensive!

Clustering

Achieve reliability and scalability by interconnecting multiple independent systems

Cluster:
A group of standard, autonomous servers configured so they appear on the network as a single machine

Single system image

Ideally…

- Bunch of off-the shelf machines
- Interconnected on a high speed LAN
- Appear as one system to users
- Processes are load-balanced across the cluster
  - May migrate
  - May run on different systems
  - All IPC mechanisms and file access available
- Fault tolerant
  - Components may fail
  - Machines may be taken down

We don't get all that (yet)

… at least not in one general purpose package

Clustering types

- Supercomputing (HPC)
  - and Batch processing
- High availability (HA)
- Load balancing
- Storage

Cluster Components

Cluster Components

- Cluster membership
- Quorum
- Configuration & service management
- Interconnect
- Storage
- Heartbeat & heartbeat network

Cluster membership

- Software to manage cluster membership
  - What are the nodes in the cluster?
  - Which nodes in the cluster are currently *alive* (active)?
- We saw this:
  - Group Membership Service in virtual synchrony
  - GFS master, HDFS Namenode
  - Bigtable master
  - Pregel master
  - MapReduce & Spark masters

Quorum

- Some members may be dead or disconnected
- **Quorum**
  - Number of elements that must be online for the cluster to function
  - Voting algorithm to determine whether the set of nodes has quorum (a majority of nodes to keep running)
- Keeping track of quorum
  - Count cluster nodes running the cluster manager
  - If over ½ are active, the cluster has quorum
  - Forcing a majority avoids **split-brain**
- We saw this with Paxos & Raft

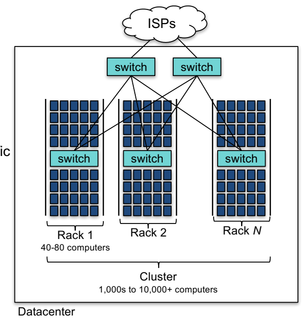
Cluster configuration & service management

- **Cluster configuration system**
  - Manages configuration of systems and software in a cluster
  - Runs in each cluster node
    - Changes propagate to all nodes
    - Administrator has a single point of control
- **Service management**
  - Identify which applications run where
  - Specify how failover occurs
    - Active: system runs a service
    - Standby: Which system(s) can run the service if the active dies
  - E.g., Map-Reduce, Pregel, Spark all use coordinators

Interconnect

Cluster Interconnect

- Provide communication between nodes in a cluster
- Goals
  - Low latency
    - Avoid OS overhead, layers of protocols, retransmission, etc.
  - High bandwidth
    - High bandwidth, switched links
    - Avoid overhead of sharing traffic with non-cluster data
  - Low CPU overhead
  - Low cost
    - Cost usually matters if you're connecting thousands of machines
- Usually a LAN is used: best $/performance ratio



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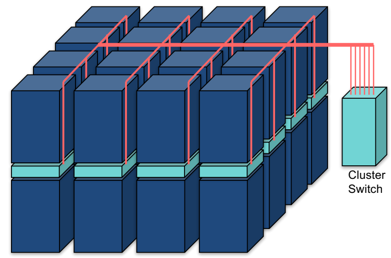
Cluster Interconnect



Cluster of 4×4 racks

Assume:
10 Gbps per server
40 servers per rack
⇒ 400 Gbps/rack

16 racks
⇒ 8 Tbps

Max switch capacity currently ~ 5 Tbps
⇒ Need at least two cluster switches

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Switches add latency

- Within one rack
  - One **switch latency** ≈ <1…8 μs for a 10 Gbps switch
  - Two links (to switch + from switch) @ 1-2 meters of cable
    - **Propagation time** in copper ≈ 2×10^8 m/s ≈ 5 ns/m
- Between racks in a cluster
  - Three switch latency (≈ <3…24 μs)
  - 4 links (to rack switch + to cluster switch + back to target rack)
  - ~10-100 meters distance (50 … 500 ns)
- Plus the normal latency of sending & receiving packets:
  - System latency of processing the packet, OS mode switch, queuing the packet, copying data to the transceiver, …
  - **Serialization delay** = time to copy packet to media ≈ 1 μs for a 1KB packet on a 10 Gbps link

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Dedicated cluster interconnects

- TCP adds latency
  - Operating system overhead, queueing, checksums, acknowledgements, congestion control, fragmentation & reassembly, …
  - Lots of interrupts
  - Consumes time & CPU resources
- How about a high-speed LAN without the overhead?
  - LAN dedicated for intra-cluster communication
    - Sometimes known as a System Area Network (SAN)
  - Dedicated network for storage: Storage Area Network (SAN)

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Example High-Speed Interconnects

Common traits
- TCP/IP Offload Engines (TOE) – TCP stack at the switch
- Remote Direct Memory Access (RDMA) – memory copy with no CPU involvement
- Intel I/O Acceleration Technology (I/OAT) – combines TOE & RDMA – data copy without CPU, TCP packet coalescing, low-latency interrupts, …

Example: **InfiniBand**
- Switch-based point-to-point bidirectional serial links
- Link processors, I/O devices, and storage
- Each link has one device connected to it
- Enables data movement via remote direct memory access (RDMA)
  - No CPU involvement!
- Up to 25 Gbps/link
  - Links can be aggregated: up to 300 Gbps with 12x aggregate

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Example High-Speed Interconnects

- Myricom's Myrinet
  - 10 Gbps Ethernet
  - PCI Express x8 connectivity
  - Low-latency, high-bandwidth, interprocess communication between nodes
  - Firmware offloads TCP functionality onto the card
    - Aggregate bandwidth of ~19.8 Gb/s
  - Example: used in IBM's Linux Cluster Solution
- IEEE 802.1 Data Center Bridging (DCB)
  - Set of standards that extend Ethernet
  - Lossless data center transport layer
    - Priority-based flow control, congestion notification, bandwidth management

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Disks

Shared storage access

- If an application can run on any machine, how does it access file data?
- If an application fails over from one machine to another, how does it access its file data?
- Can applications on different machines share files?

Network (Distributed) File Systems

One option:
- Network file systems: NFS, SMB, AFS, AFP, etc.
- Works great for many applications

- Concerns
  - Availability
    - Address with replication (most file systems offer little)
  - Performance
    - Remote systems on a LAN vs. local bus access
    - Overhead of remote operating system & network stack
    - Point of congestion
    - Look at GFS/HDFS to distribute file data across lots of servers … or other parallel file systems, such as Lustre, GlusterFS, or Ceph

Shared disks & Cluster file systems

- Shared disk
  - Allows multiple systems to share access to disk drives
  - Works well if there isn't much contention
- **Cluster File System**
  - Client runs a file system accessing a shared disk at the **block level**
    - *vs. a distributed file system, which access at a file-system level*
  - No client/server roles, no disconnected modes
  - All nodes are peers and access a shared disk(s)
  - **Distributed Lock Manager (DLM)**
    - Process to ensure mutual exclusion for disk access
    - Provides inode-based locking and caching control
    - Not needed for local file systems on a shared disk

Cluster File Systems

- Examples:
  - IBM General Parallel File System (GPFS)
  - Microsoft Cluster Shared Volumes (CSV)
  - Oracle Cluster File System (OCFS)
  - Red Hat Global File System (GFS2)
- Linux GFS2 (no relation to Google GFS)
  - Cluster file system accessing storage at a **block level**
  - Cluster Logical Volume Manager (CLVM): volume management of cluster storage
  - Global Network Block Device (GNBD): block level storage access over ethernet: cheap way to access block-level storage

The alternative: shared nothing

Shared nothing
- No shared devices
- Each system has its own storage resources
- No need to deal with DLMs
- If a machine A needs resources on B, A sends a message to B
  - If B fails, storage requests have to be switched over to a live node

- Need exclusive access to shared storage
  - Multiple nodes may have access to shared storage
  - Only one node is granted exclusive access at a time – *one owner*
  - Exclusive access changed on failover

SAN: Computer-Disk interconnect

- Storage Area Network (SAN)
- Separate network between nodes and storage arrays
  – Fibre channel
  – iSCSI
- Any node can be configured to access any storage through a fibre channel switch
- Acronyms
  – DAS: Direct Attached Storage
  – SAN: block-level access to a disk via a network
  – NAS: file-level access to a remote file system (NFS, SMB,…)

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Failover

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HA issues

- How do you detect failover?
- How long does it take to detect?
- How does a dead application move/restart?
- Where does it move to?

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Heartbeat network

- Machines need to detect faulty systems
  – **Heartbeat**: Periodic "ping" mechanism
  – An "are you alive" message
- Need to distinguish ***system faults*** from ***network faults***
  – Useful to maintain redundant networks
  – Avoid split-brain issues in systems without quorum (e.g., a 2-node cluster)
- Once you know who is dead or alive, then determine a course of action

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Failover Configuration Models

- Active/Passive
  – Requests go to active system
  – Passive nodes do nothing until they're needed
  – Passive nodes maintain replicated state (e.g., SMR/Virtual Synchrony)
  – Example: Chubby
- Active/Active
  – Any node can handle a request
  – Failed workload goes to remaining nodes
  – Replication must be *N*-way for *N* active nodes
- Active/Passive: *N+M*
  – *M* dedicated failover node(s) for *N* active nodes

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Design options for failover

- **Cold failover**
  – Application restart
  – *Example: map and reduce workers in MapReduce*
- **Warm failover**
  – Restart last checkpointed image
  – Relies on application checkpointing itself periodically
  – *Example: Pregel*
- **Hot failover**
  – Application state is synchronized across systems
    - E.g., replicated state machines or lockstep synchronization at the CPU level
  – Spare is ready to run immediately
  – May be difficult at a fine granularity, prone to software faults (e.g., what if a specific set of inputs caused the software to die?)
  – *Example: Chubby*

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Design options for failover

- With either type of failover …
- **Multi-directional failover**
  - Failed applications migrate to / restart on available systems
- **Cascading failover**
  - If the backup system fails, application can be restarted on another surviving system

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IP Address Takeover (IPAT)

Depending on the deployment:

- **Ignore**
  - IP addresses of services don't matter. A load balancer, name server, or coordinator will identify the correct machine
- **Take over IP address**
  - A node in an active/passive configuration may need to take over the IP address of a failed node
- **Take over MAC address**
  - MAC address takeover may be needed if we cannot guarantee that other nodes will flush their ARP cache
- **Listen on multiple addresses**
  - A node in an active/active configuration may need to listen on multiple IP addresses

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Hardware support for High Availability

- Hot-pluggable components
  - Minimize downtime for component swapping
  - E.g., disks, power supplies, CPU/memory boards
- Redundant devices
  - Redundant power supplies
  - Parity on memory
  - Mirroring on disks (or RAID for HA)
  - Switchover of failed components
- Diagnostics
  - On-line identification & service

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Fencing

- Fencing: method of isolating a node from a cluster
  - Apply to failed node
  - Disconnect I/O to ensure data integrity
  - Avoid problems with Byzantine failures
  - Avoids problems with *fail-restart*
    - Restarted node has not kept up to date with state changes
- Types of fencing
  - Power fencing: shut power off a node
  - SAN fencing: disable a Fibre Channel port to a node
  - Disable access to a global network block device (GNBD) server
  - Software fencing: remove server processes from the group
    - E.g., virtual synchrony

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Cluster software hierarchy

Example: Windows Server cluster abstractions

Top tier: Cluster abstractions
- Failover manager (what needs to be started/restarted?
- Resource monitor (what's going on?)
- Cluster registry (who belongs in the cluster?)

Middle tier: Distributed operations
- Global status update
- Membership
- Quorum (leader election)

Bottom tier: OS and drivers
- Cluster disk driver, cluster network drivers
- IP address takeover

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High Performance Computing (HPC)

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Supercomputers

- Most powerful supercomputer: 94 petaflops
  - Sunway TaihuLight – *National Supercomputing Center in Wuxi, China*
  - 40,960 1.45 GHz SW26010 64-bit RISC processors
  - Each processor contains 260 processing cores
  - 40 cabinets
  - Interconnect built into the chip
  - Runs Linux (Raise)

Titan Supercomputer: #5 on the list

- **Titan**, Oak Ridge National Laboratories
- Heterogeneous computing: GPUs + conventional CPUs
- 18,688 Cray XK6 compute nodes
  - Each node:
    - One AMD 16-core Opteron 6274 CPU @ 2.2 GHz
    - 32 GB DDR3 memory
    - Cray's Gemini network
  - 18,688 nodes are augmented with:
    - NVIDIA Tesla Kepler K20 GPU application processor
      - K20 has 2,688 CUDA cores (7.1 billion transistors per GPU)
- Peak performance: > 20 petaFLOPS (10^{15} FLOPS)

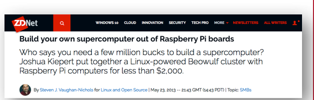
Titan

- OS
  - Cray Linux Environment (based on SUSE 11)
  - Some cores are dedicated to OS tasks so that apps on other cores are not interrupted by the OS
  - Batch job scheduling (Moab and Torque)
- Total:
  - 299,008 AMD Opteron CPU cores
  - 710 TB total system memory
  - Connected to a 240 GB/s Spider file system with 10 petabytes
    - 10,000 1TB 7200rpm 2.5" hard drives
  - Total transistor count: 177 trillion!
  - Total power consumption: 7 (typical) - 9 megawatts (peak)

- Supercomputers are *not* distributed computers
- Lots of processors connected by high-speed networks
- Shared memory access
- Shared operating system (all TOP500 run Linux)

Supercomputing clusters

- Supercomputing cluster
  - Build a supercomputer from commodity computers & networks
  - A distributed system



Build your own supercomputer out of Raspberry Pi boards

Who says you need a few million bucks to build a supercomputer? Joshua Kiepert put together a Linux-powered Beowulf cluster with Raspberry Pi computers for less than $2,000.

By Steven J. Vaughan-Nichols for Linux and Open Source | May 23, 2013 -- 21:43 GMT (14:43 PDT) | Topic: SMBs

- Target complex, typically scientific, applications:
  - Large amounts of data
  - Lots of computation
  - Parallelizable application
- Many custom efforts
  - Typically Linux + message passing software + remote exec + remote monitoring

Programming tools: MPI

MPI: Message Passing Interface

- API for sending/receiving messages
  - Optimizations for shared memory & NUMA
  - Group communication support
- Other features:
  - Scalable file I/O
  - Dynamic process management
  - Synchronization (barriers)
  - Combining results

Programming tools: PVM

- **PVM**: Parallel Virtual Machine
- Software that emulates a general-purpose heterogeneous computing framework on interconnected computers
- Model: app = set of tasks
  - Functional parallelism: tasks based on function: input, solve, output
  - Data parallelism: tasks are the same but work on different data
- PVM presents library interfaces to:
  - Create tasks
  - Use global task IDs
  - Manage groups of tasks
  - Pass basic messages between tasks

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Clustering for performance

- Example: Early (>20 years old!) effort on Linux – Beowulf
  - Initially built to address problems associated with large data sets in Earth and Space Science applications
  - From Center of Excellence in Space Data & Information Sciences (CESDIS)
    - Division of University Space Research Association at the Goddard Space Flight Center
  - Still used!
- This isn't one fixed package
  - Just an example of putting tools together to create a supercomputer from commodity hardware

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What makes it possible?

- Commodity off-the-shelf computers are cost effective
- Publicly available software:
  - Linux, GNU compilers & tools
  - MPI (message passing interface)
  - PVM (parallel virtual machine)
- Low cost, high speed networking
- Experience with parallel software
  - Difficult: solutions tend to be custom

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What can you run?

- Programs that do not require fine-grain communication
- Basic properties
  - Nodes are dedicated to the cluster
    - Performance of nodes not subject to external factors
  - Interconnect network isolated from external network
    - Network load is determined only by application
  - Global process ID provided
    - Global signaling mechanism

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Beowulf configuration

Includes:
- BProc: Beowulf distributed process space
  - Start processes on other machines
  - Global process ID, global signaling
- Network device drivers
  - Channel bonding, scalable I/O
- File system (file sharing is generally not critical)
  - NFS root
  - unsynchronized
  - synchronized periodically via rsync

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Beowulf programming tools

- PVM and MPI libraries
- Distributed shared memory
  - Page based: software-enforced ownership and consistency policy
- Cluster monitor
- Global *ps*, *top*, *uptime* tools
- Process management
  - Batch system
  - Write software to control synchronization and load balancing with MPI and/or PVM
  - Job scheduling: use something like HTCondor or Mosix

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Another example

- Rocks Cluster Distribution
  - Employed on over 1,300 clusters
  - Mass installation is a core part of the system
    - Mass re-installation for application-specific configurations
  - Front-end central server + compute & storage nodes
  - Based on CentOS Linux
  - Rolls: collection of packages
    - Base roll includes: PBS (portable batch system), PVM (parallel virtual machine), MPI (message passing interface), job launchers, …

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Another example: Microsoft HPC Pack

- Clustering package for Windows & Windows Server
  - Supports on-premises & on-demand computers deployed in Azure
- Systems Management
  - Management Console: plug-in to System Center UI with support for Windows PowerShell
  - RIS (Remote Installation Service)
- Networking
  - MS-MPI (Message Passing Interface)
  - ICS (Internet Connection Sharing) : NAT for cluster nodes
  - Network Direct RDMA (Remote DMA)
- Job scheduler
- Storage: iSCSI SAN and SMB support
- Failover support

See http://www.microsoft.com/hpc/en/us/product/cluster-computing.aspx

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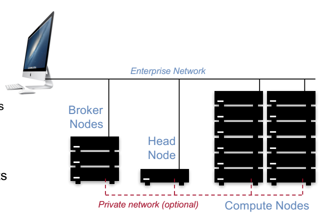
Microsoft HPC Pack

- Head node
  - Cluster management
  - Provides failover
  - Mediates access to cluster
  - Job scheduler
    - Queues jobs
    - Initiates tasks on compute nodes
    - Monitors status of jobs & nodes
- Broker nodes
  - Load balances service requests
  - Return results to client
- Compute nodes
  - Carry out work assigned by job scheduler



See http://www.microsoft.com/hpc/en/us/product/cluster-computing.aspx

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Batch Processing

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Batch processing

- Non-interactive processes
  - Schedule, run eventually, collect output
- Examples:
  - MapReduce, many supercomputing tasks (circuit simulation, climate simulation, physics simulation)
  - Graphics rendering
    - Maintain a queue of frames to be rendered
    - Have a dispatcher to remotely exec process
- In many cases – minimal or no IPC needed
- Coordinator dispatches jobs

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Single-queue work distribution: Render Farms

Examples:

- Pixar:
  - 12,500 cores on Dell render blades running Linux and Renderman
  - Custom Linux software for articulating, animating/lighting (Marionette), scheduling (Ringmaster), and rendering (RenderMan)
  - Average time to render a single frame
    - Cars (2006): 8 hours
    - Cars 2 (2011): 11.5 hours
    - Monsters University (2013): 29 hours 100 million CPU hours for the whole movie!
- DreamWorks:
  - Thousands of HP Z820 workstations
    - 32-96 GB RAM, 160 FB SSD boot drive + 500 GB data drive, Nvidia Quadro 5000 (352 cores)
    - Movie file may use 250 TB for storage
  - Kung Fu Panda 2 used 100 TB data and required over 55 million render hours
  - Shrek 3: 20 million CPU render hours. Platform LSF used for scheduling + Maya for modeling + Avid for editing+ Python for pipelining – movie uses 24 TB storage

http://venturebeat.com/2013/04/24/the-making-of-pixars-latest-technological-marvel-monsters-university/2/
http://news.cnet.com/8301-13772_3-20068109-52/new-technology-revs-up-pixars-cars-2/

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Single-queue work distribution: Render Farms

- Disney Animation's render farm (2014)
  - Hardware
    - Spread across four sites
    - Over 55,000 Intel cores
    - 500 TB memory
    - Uses about 1.5 MW of power
    - Linked with 10 Gb Ethernet
    - All non-volatile storage is SSD
  - In-house CODA job distribution system
    - Typically performs 1.1 million render hours per day (hundreds of thousands of tasks)

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Batch Processing

- OpenPBS.org:
  - Portable Batch System
  - Developed by Veridian MRJ for NASA
- Commands
  - *Submit job scripts*
    - Submit interactive jobs
    - Force a job to run
  - *List jobs*
  - *Delete jobs*
  - *Hold jobs*

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Load Balancing

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Functions of a load balancer

- Load balancing
- Failover
- Planned outage management

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Redirection

Simplest technique

HTTP REDIRECT error code

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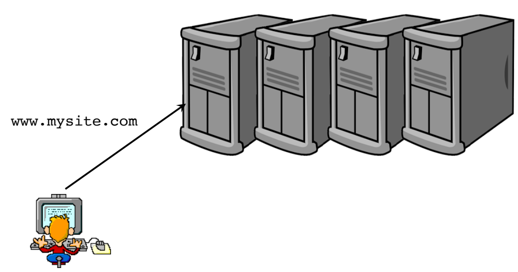
Redirection

Simplest technique

HTTP REDIRECT error code



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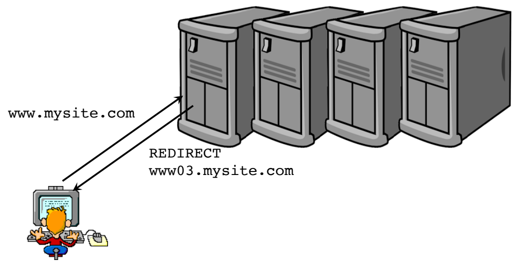
Redirection

Simplest technique

HTTP REDIRECT error code



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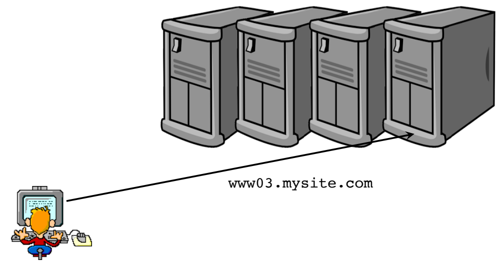
Redirection

Simplest technique

HTTP REDIRECT error code



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Redirection

- Trivial to implement
- Successive requests automatically go to the same web server
  - Important for sessions
- Visible to customer
  - Don't like the changing URL
- Bookmarks will usually tag a specific site

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Load balancing router

As routers got smarter

- Not just simple packet forwarding
- Most support packet filtering
- Add load balancing to the mix

- This includes most IOS-based Cisco routers, Altheon, F5 Big-IP

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Load balancing router

- Assign one or more virtual addresses to physical address
  - Incoming request gets mapped to physical address
- Special assignments can be made per port
  - e.g., all FTP traffic goes to one machine
- **Balancing decisions:**
  - Pick machine with least # TCP connections
  - Factor in weights when selecting machines
  - Pick machines round-robin
  - Pick fastest connecting machine (SYN/ACK time)
- **Persistence**
  - Send all requests from one user session to the same system

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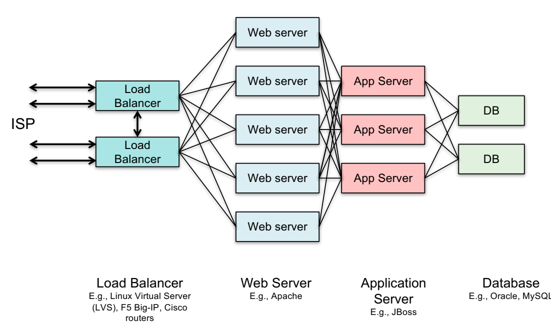
Load Balancing



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DNS-based load balancing

- Round-Robin DNS
  - Respond to DNS requests with a list of addresses instead of one
  - The order of the list is permuted with each response
- Geographic-based DNS response
  - Multiple clusters distributed around the world
  - Balance requests among clusters
  - Favor geographic proximity
  - Examples:
    - BIND with Geodns patch
    - PowerDNS with geobackend
    - Amazon Route 53

The end

