Distributed Systems

24. Clusters

Paul Krzyzanowski
Rutgers University
Fall 2016

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 = High Performance Computing)
  - 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
  - Bigtable master
  - Pregel master

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

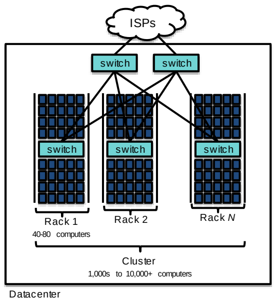
Cluster configuration & service management

- **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

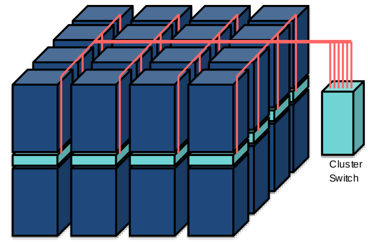
Interconnect

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



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

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

Dedicated cluster interconnects

- TCP adds latency!
  - Operating system overhead, 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)

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, …
- 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

Example High-Speed Interconnects

- 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
- 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

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

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 (SSD/disk in a computer)
  - SAN: block-level access to a disk via a dedicated storage network
  - NAS: file-level access to a remote file system (NFS, SMB,…)

Failover

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?

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

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

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*

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

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

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

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

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

High Performance Computing (HPC)

Titan Supercomputer

- Oak Ridge National Laboratories Titan
- 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)

Supercomputing clusters

- 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

Clustering for performance

- Example: Early 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
- This isn't one fixed package
  - Just an example of putting tools together to create a supercomputer from commodity hardware

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

What can you run?

- Programs that do not require fine-grain communication
- 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

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

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

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, …

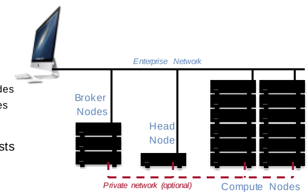
Another example: Microsoft HPC Pack

- Clustering package for Windows & Windows Server
- 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

Microsoft HPC Pack 2012

- 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

Batch Processing

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

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-monstersuniversity/2/
http://news.cnet.com/8301-13772_3-20068109-52/new-technology-revs-up-pixars-cars-2/

Single-queue work distribution: Render Farms

- Disney Animation's render farm (2013)
  - Hardware
    - Spread across four sites
    - Over 55,000 Intel cores
    - 500 TB memory
    - Uses about 1.5 MW of pwer
    - 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)

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*

Load Balancing

Functions of a load balancer

- Load balancing
- Failover
- Planned outage management

Redirection

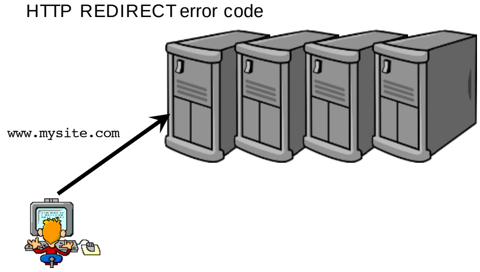
Simplest technique

HTTP REDIRECT error code

Redirection

Simplest technique

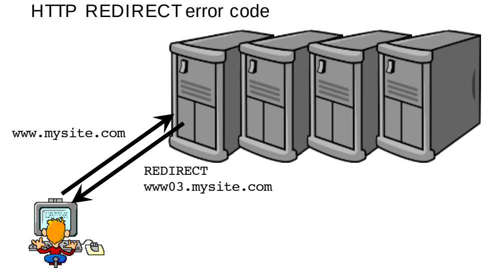
HTTP REDIRECT error code



Redirection

Simplest technique

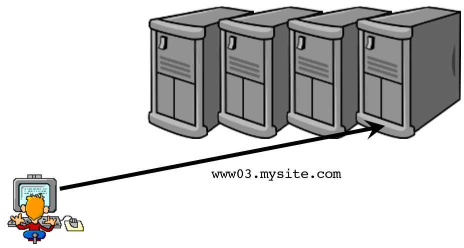
HTTP REDIRECT error code



Redirection

Simplest technique

HTTP REDIRECT error code



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

Load balancing router

As routers got smarter

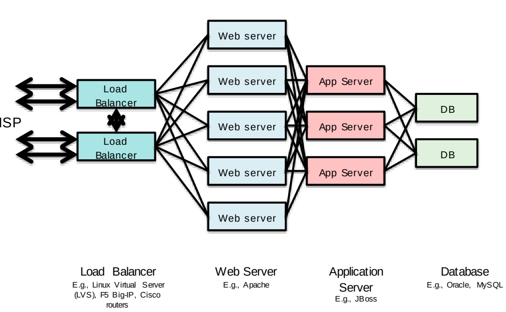
- Not just simple packet forwarding
- Most support packet filtering
- Add load balancing to the mix

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

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

Load Balancing



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