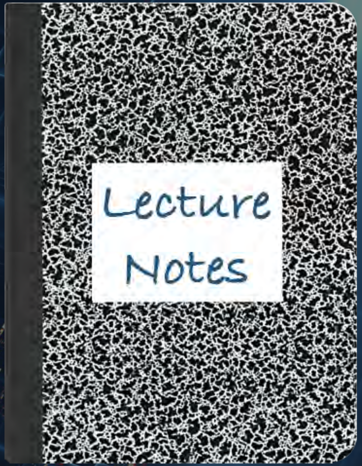
CS 417 – DISTRIBUTED SYSTEMS



Week 12: Infrastructure

High Performance Computing (HPC) Clusters

Paul Krzyzanowski

Supercomputers

2021's most powerful supercomputer: Fugaku 富岳 – Japan – developed by RIKEN & Fujitsu

- Performance
  - 442 petaflops
  - Fujitsu A64FX SoC processors: 7.6 million ARM cores
- OS
  - Compute nodes run McKernel (lightweight kernel designed for HPC) – a few hundred lines of C++
  - Communicate with I/O nodes that run Linux
- Communication
  - Torus Fusion (tofu) – proprietary interconnect developed by Fujitsu
    - 6-dimensional mesh/torus topology – full-duplex link with peak bandwidth of 5 GB/s in each direction
- Storage
  - 1.6 TB NVMe SSD for every 16 nodes
  - 150 PB shared storage – Lustre FS

https://en.wikipedia.org/wiki/Fugaku_(supercomputer)

Supercomputers

2018's Most powerful supercomputer:
IBM AC922 – Summit at *Oak Ridge National Laboratory*

- 189 petaflops, >10PB memory
- 4,608 nodes
  - 6 NVIDIA Volta V100s GPUs
  - 2 IBM POWER9™ CPUs
  - 512 GB DDR4 + 96GB HBM2 RAM
  - 1600GB NV memory
  - 42 teraflops per node

>27,000 GPUs
>9,000 CPUs

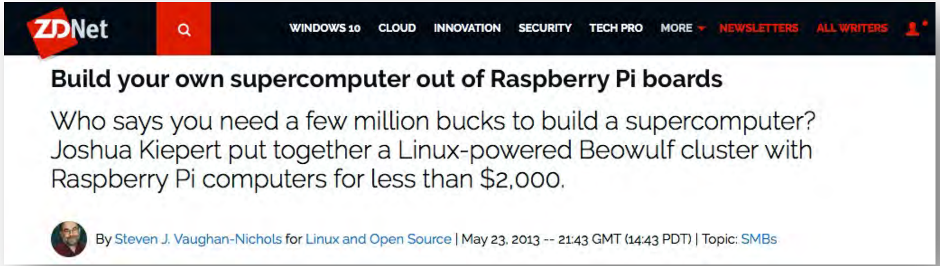
- 100G InfiniBand interconnect
- 250 PB 2.5 TB/s file system
- OS: Red Hat Enterprise Linux
- Peak power consumption: 13 MW

See https://www.olcf.ornl.gov/summit/

- 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



ZDNet WINDOWS 10 CLOUD INNOVATION SECURITY TECH PRO MORE NEWSLETTERS ALL WRITERS

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

Cluster Interconnects

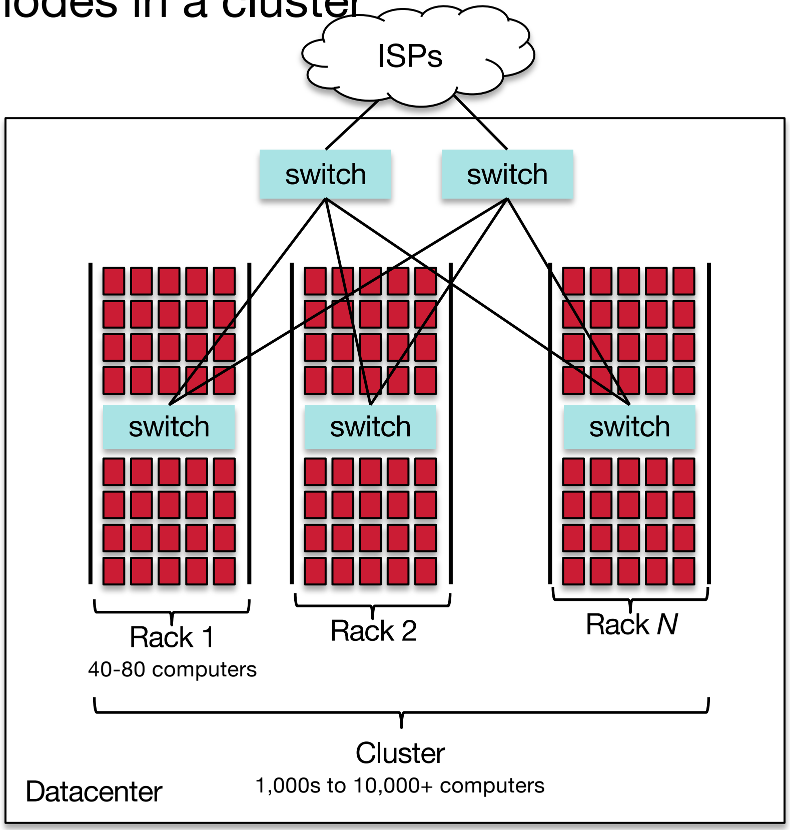
Cluster Interconnect

Provide communication between nodes in a cluster

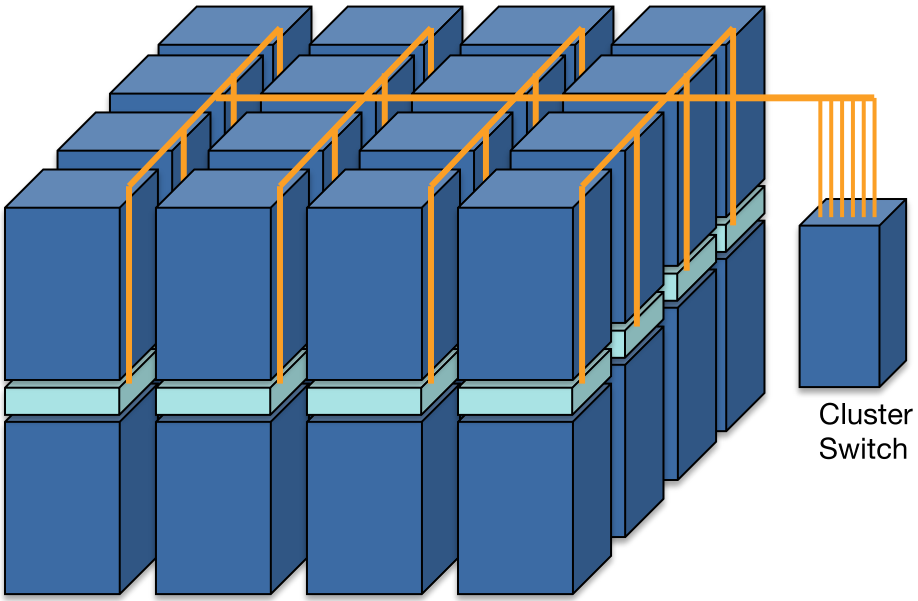
Goals

- 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)

Add to that 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, queueing, checksums, acknowledgements, congestion control, fragmentation & reassembly, …
- Lots of interrupts
- Consumes time & CPU resources

How about using 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 network card
- **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 High-Speed Interconnects

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 250 Gbps/link
  - Links can be aggregated: up to 3000 Gbps with 12x links

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

Programming tools for HPC: 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

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

HPC Cluster Example

Early 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

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

- 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

HPC Cluster Example openHPC

`http://openhpc.community`

- 18 admin tools
- 3 compiler families (GNU, Intel, LLVM)
- 13 development tool packages (EasyBuild, cbuild, libtool, …)
- Lua scripting language & supporting packages
- 8 I/O libraries
  - Adios – enables defining how data is accessed
  - HDF5 – data model, library, and file format for storing and managing data
  - NetCDF – managing array-oriented scientific data
- Lustre file system
- 4 MPI packages
- 12 parallel libraries
- 14 performance tools
- Provisioning tools, resource management, runtime packages
- 6 threaded library packages

HPC example: Rocks Cluster Distribution

- Employed on over 1,900 clusters (https://app.awesome-table.com/-KIAGPC-2IYjjVG2ReJn/view)
- 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, …

Open-source Linux cluster distribution – supported by the National Science Foundation – rocksclusters.org

Batch Processing

Batch processing

- Non-interactive processes
  – Schedule, run eventually, collect output
- Examples:
  – MapReduce, many supercomputing tasks (circuit simulation, climate simulation, weather)
  – 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

Example – Pixar:

- 55,000 cores running RedHat Linux and Renderman (2018)
- Custom Linux software for articulating, animating/lighting (Marionette), scheduling (Ringmaster), and rendering (RenderMan)

- Toy Story
  - Each frame took between 45 minutes to 30 hours to render: 114,240 total frames
  - 117 computers running 24 hours a day
  - Toy Story 4 – 24 years later: 50-150 hours to render each frame
- Took over two years (in real time) to render Monsters University (2013)
  - Sully has over 1 million hairs – each rendered distinctly & motion animated
- Average time to render a single frame
  - Cars (2006): 8 hours
  - Cars 2 (2011): 11.5 hours
  - Disney/Pixar's Coco – Up to 100 hours to render one frame

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

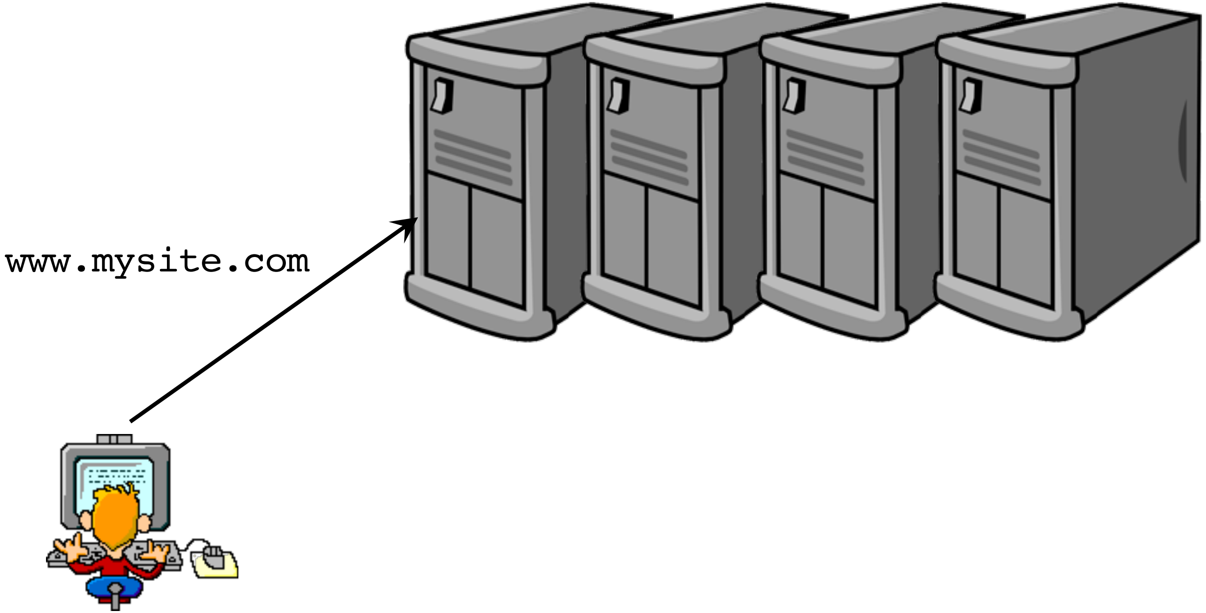
Simplest technique

- HTTP REDIRECT error code

Redirection

Simplest technique

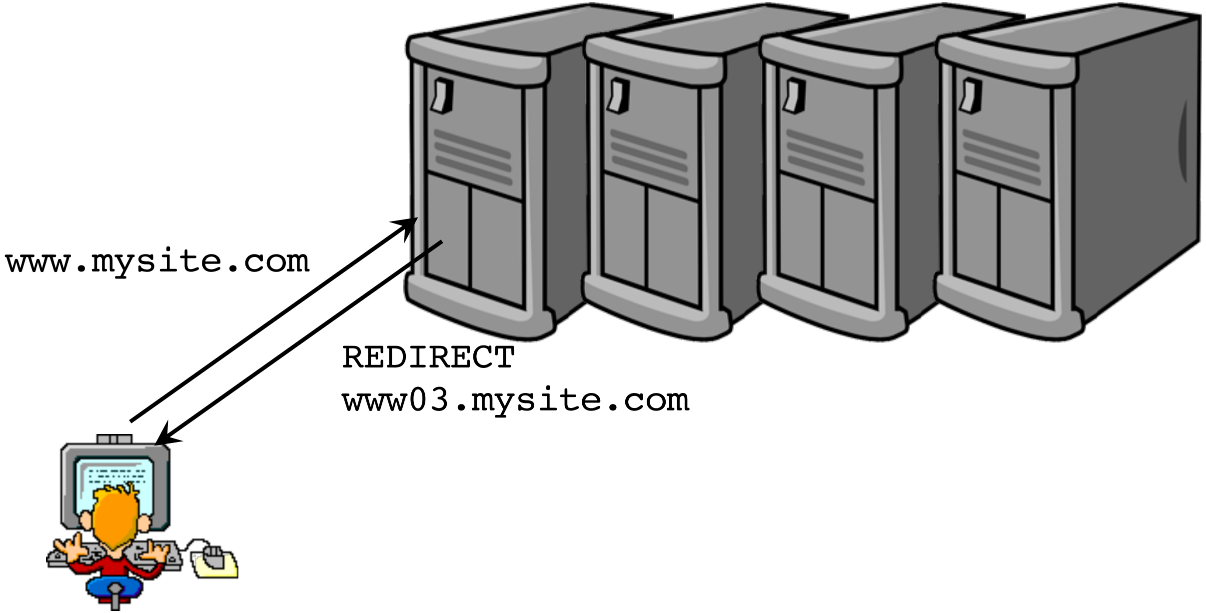
HTTP REDIRECT error code



Redirection

Simplest technique

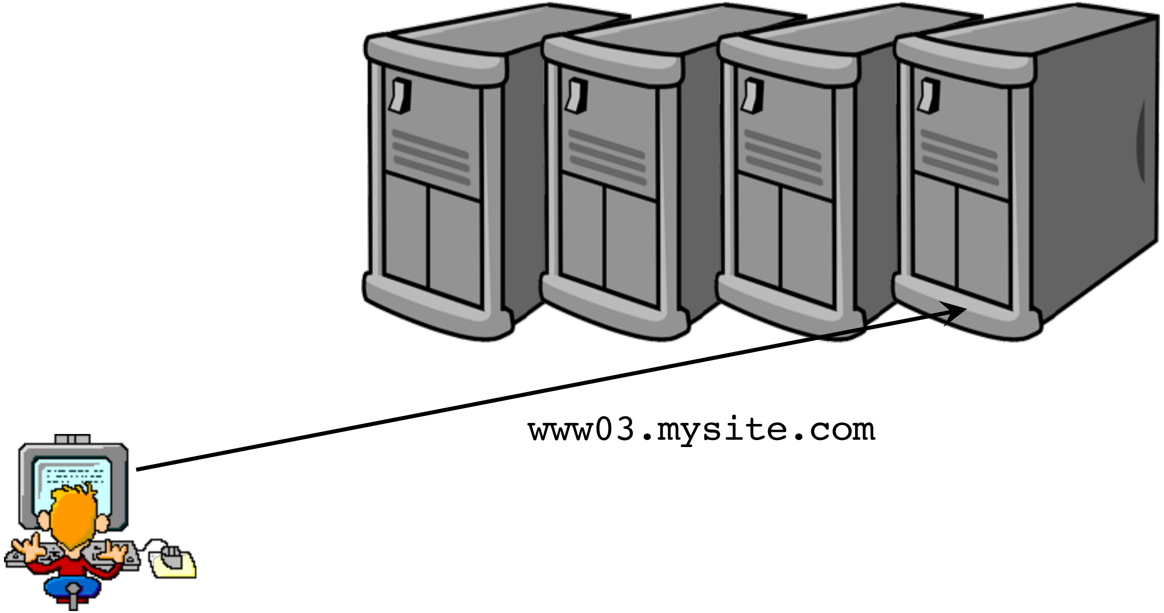
HTTP REDIRECT error code



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, Radware Alteon, 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

DNS-based load balancing

- Round-Robin DNS
  - Respond to DNS requests with different addresses
    … or a list of addresses instead of one address
    but 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 Geo backend
    - Amazon Route 53

The End