TCSS 558: APPLIED DISTRIBUTED COMPUTING

Chapter 3 - Processes

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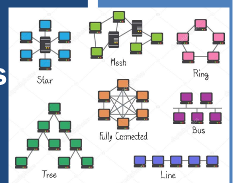

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OBJECTIVES

- Assignment 0 – questions
- Assignment 1 – questions
- Feedback from 2/4
- Chapter 3.3: Clients – cont'd
- Chapter 3.4: Servers
- Chapter 3.5: Resource Migration

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MIDTERM SCHEDULING SURVEY

- **TCSS 558B**
- Tuesday February 11 – 6 respondents (32%)
- Thursday February 13 – 7 respondents (37%) *(Internship fair @UW Seattle)*
- **Tuesday February 18 – 12 respondents (63%)** √
- No Preference – 2 respondents (11%)

- **Midterm Plan:**
- Content coverage - through 1st half of Lecture 11 on Feb 11th
- Practice midterm - 2nd half of Lecture 11 on Feb 11th
- February 13th – Will cover new material not on midterm
- Midterm Exam – Tuesday February 18th
- Exams returned no later than Tuesday February 25th

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (9 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.69 (up from 6.11)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.81 (up from 5.22)**

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FEEDBACK FROM 2/4

- ***In finite state machine server, while I/O is reading/writing, there should be a thread executing I/O operation, how is this considered single thread?***
- The server is a "finite state machine"

an abstract machine that can be in exactly one of a finite number of states at any given time

- Server has just one thread of execution
- Client requests arrive: if processing the request requires I/O (disk or network), all I/O is non-blocking
  - I/O request issued as asynchronous call to operating system
  - I/O is processed using separate kernel thread (protected mode)
  - Server saves state of client request, "switches" to work on other request
  - Operating system generates interrupt when I/O completes
  - Server traps interrupt, "switches" back to original request who's I/O is complete

  … *(Section 3.1, p. 115)*

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FEEDBACK - 2

- ***About virtualization, can you introduce something about Firecracker?***
- Firecracker is a MicroVM designed to host FaaS functions / containers for serverless computing
- **Goal**: securely share servers with many users simultaneously running serverless workloads
- Features accelerated kernel loading
- microVMs runs with reduced memory overhead of 5 MB/VM
- Implements minimal device model excluding non-essential functionality
- Firecracker runs in user space (kernel not exposed to VMM)
- Very fast VM startup time: ~125 ms, up to 150 VMs/sec/host
- Leverages KVM virtualization to ensure workload isolation
- See: https://firecracker-microvm.github.io/

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FEEDBACK - 2

- ***About virtualization, can you introduce something about Firecracker?***
- Firecracker is a MicroVM designed to host FaaS functions /

Key take-away:

Firecracker provides VM like experience (security/isolation) ***with*** container like agility (high speed, low overhead)

- Firecracker runs in user space (kernel not exposed to VMM)
- Very fast VM startup time: ~125 ms, up to 150 VMs/sec/host
- Leverages KVM virtualization to ensure workload isolation
- https://firecracker-microvm.github.io/

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FIRECRACKER (EXTRA)

- Can pack thousands of VMs onto single machine
- VMs feature rate limiter to optimize sharing of network & storage
  - VMs traditionally provide intelligent scheduling/sharing of CPU/memory
  - Firecracker goes further with network/storage sharing
- Can virtualize Linux 4.14+ and OSv guests
- Firecracker is a VMM that is an alternative to QEMU
- Replaces QEMU which underlies KVM
- QEMU –hosted VMM that performs hardware virtualization
- Early 2000s command line tool for creating VMs on Linux
- QEMU supports multiple modes:
  - System emulation (provides the full VM)
  - KVM mode (handles disk image setup/migration and some HW emulation, KVM executes (runs) the VM)
  - Xen mode (emulates some HW, XEN executes (runs) the VM)
- Firecracker is based on Chromium OS's VMM called crossvm
- Firecracker is written in Rust
  - Rust - new language designed for safe concurrency

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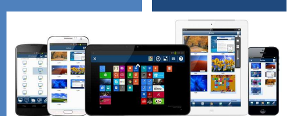

CH. 3.3: CLIENTS

L10.9

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TYPES OF CLIENTS

- Thick clients
  - Web browsers
    - Client-side scripting
  - Mobile apps
  - Multi-tier MVC apps
- Thin clients
  - Remote desktops/GUIs (very thin)

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RDP VS. VNC

- **VNC** sends picture of desktop across network
- Minimal optimizations are employed
  - Send only parts of screen which have changed
  - Limit colors, resolution
- VNC requires more data transfer
- **RDP** sends instructions on how to draw screen to client
- Client renders image based on instructions and displays it
- Transferring instructions requires much less network bandwidth
- Client computer "understands" image it has created
- Client performs simple operations locally
  - Move windows without sending mouse input to host computer
  - No need to wait for host computer to render moved window
  - No need to wait for response from server
  - Client just calculates and draws results locally

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THIN CLIENTS

- Thin clients
  - X windows protocol
  - A variety of other remote desktop protocols exist:

Remote desktop protocols include the following:

- Apple Remote Desktop Protocol (ARD) – Original protocol for Apple Remote Desktop on macOS machines.
- Appliance Link Protocol (ALP) – a Sun Microsystems-specific protocol featuring audio (play and record), remote printing, remote USB, accelerated video
- HP Remote Graphics Software (RGS) – a proprietary protocol designed by Hewlett-Packard specifically for high end workstation remoting and collaboration.
- Independent Computing Architecture (ICA) – a proprietary protocol designed by Citrix Systems
- NX technology (NoMachine NX) – Cross platform protocol featuring audio, video, remote printing, remote USB, H264-enabled.
- PC-over-IP (PCoIP) – a proprietary protocol used by VMware (licensed from Teradici)[2]
- Remote Desktop Protocol (RDP) – a Windows-specific protocol featuring audio and remote printing
- Remote Frame Buffer Protocol (RFB) – A framebuffer level cross-platform protocol that VNC is based on.
- SPICE (Simple Protocol for Independent Computing Environments) – remote-display system built for virtual environments by Qumranet, now Red Hat
- Splashtop – a high performance remote desktop protocol developed by Splashtop, fully optimized for hardware (H.264) including Intel / AMD chipsets, NVIDIA of media codecs, Splashtop can deliver high frame rates with low latency, and also low power consumption.
- X Window System (X11) – a well-established cross-platform protocol mainly used for displaying local applications; X11 is network transparent

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THIN CLIENTS - 2

- Applications should separate application logic from UI
- When application logic and UI interaction are tightly coupled many requests get sent to X kernel
- Client must wait for response
- Synchronous behavior and app-to-UI coupling adversely affects performance over WAN / Internet

- **Protocol optimizations**: reduce bandwidth by shrinking size of X protocol messages
- Send only differences between messages with same identifier
- Optimizations enable connections with 9600 kbps

THIN CLIENTS - 3

- Virtual network computing (VNC)
- Send display over the network at the pixel level (instead of X lib events)
- Reduce pixel encodings to save bandwidth – fewer colors
- Pixel-based approaches loose application semantics
- Can transport any GUI this way

- **THINC**- hybrid approach
- Send video device driver commands over network
- More powerful than pixel based operations
- Less powerful compared to protocols such as X

TRADEOFFS: ABSTRACTION OF REMOTE DISPLAY PROTOCOLS

- Tradeoff space: abstraction level of remote display protocols
  - Examples: VNC, THINC, RDP, X11

Pixel-level VNC ←——→ **Graphics lib** X11 / RDP

TRADEOFFS: ABSTRACTION OF REMOTE DISPLAY PROTOCOLS

- Tradeoff space: abstraction level of remote display protocols
  - Examples: VNC, THINC, RDP, X11

Pixel-level VNC ←——→ **Graphics lib** X11 / RDP

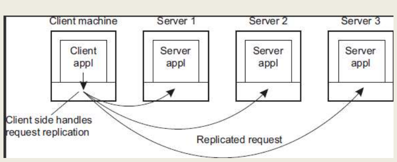
Pixel-level:
- Generic – no app context
- Graphics data
- Higher network bandwidth
- Fewer colors
- Utilize graphics compression
- More network traffic
- Server more processing

Graphics lib:
- Application context is available
- UI data/operations
- Lower network bandwidth
- More colors
- Client more processing

CLIENT ROLES IN PROVIDING DISTRIBUTION TRANSPARENCY

- Clients help enable distribution transparency of servers

- Replication transparency
  - Client aggregates responses from multiple servers
  - Client application (not users) know of replicas



CLIENT ROLES IN PROVIDING DISTRIBUTION TRANSPARENCY - 2

- Location/relocation/migration transparency
  - Harness convenient naming system to allow client to infer new locations
  - Server inform client of moves / Client reconnects to new endpoint
  - Client hides network address of server, and reconnects as needed
  - May involve temporary loss in performance
- Replication transparency
  - Client aggregates responses from multiple servers
- Failure transparency
  - Client retries, or maps to another server, or uses cached data
- Concurrency transparency
  - Transaction servers abstract coordination of multithreading

CH. 3.4: SERVERS

SERVERS

- Cloud & Distributed Systems – rely on **Linux**
- http://www.zdnet.com/article/it-runs-on-the-cloud-and-the-cloud-runs-on-linux-any-questions/
- IT is moving to the cloud. And, what powers the cloud?
  - **Linux**
- Uptime Institute survey - 1,000 IT executives (2016)
  - 50% of IT executives – plan to migrate majority of IT workloads to off-premise to cloud or colocation sites
  - 23% expect the shift in 2017, 70% by 2020…
- Docker on Windows / Mac OS X
  - Based on **Linux**
  - Mac: Hyperkit Linux VM
  - Windows: Hyper-V Linux VM

SERVERS - 2

- Servers implement a specific service for a collection of clients
- Servers wait for incoming requests, and respond accordingly

- **Server types**
- **Iterative**: immediately handle client requests
- **Concurrent**: Pass client request to separate thread

- Multithreaded servers are concurrent servers
  - E.g. Apache Tomcat

- ***Alternative***: fork a new **process** for each incoming request
- ***Hybrid***: mix the use of multiple processes with thread pools

END POINTS

- Clients connect to servers via: **IP Address** and **Port Number**
- How do ports get assigned?
  - Many protocols support "default" port numbers
  - Client must find IP address(es) of servers
  - A single server often hosts multiple end points (servers/services)
  - When designing new TCP client/servers must be careful not to repurpose ports already commonly used by others

COMMON PORTS

packetlife.net

TCP/UDP Port Numbers

7	Echo	**554**	RTSP	**2745**	Bagle.H	**6891-6901**	Windows Live
19	Chargen	**546-547**	DHCPv6	**2967**	Symantec AV	**6970**	Quicktime
20-21	FTP	**560**	rmonitor	**3050**	Interbase DB	**7212**	GhostSurf
22	SSH/SCP	**563**	NNTP over SSL	**3074**	XBOX Live	**7648-7649**	CU-SeeMe
23	Telnet	**587**	SMTP	**3124**	HTTP Proxy	**8000**	Internet Radio
25	SMTP	**591**	FileMaker	**3127**	MyDoom	**8080**	HTTP Proxy
42	WINS Replication	**593**	Microsoft DCOM	**3128**	HTTP Proxy	**8086-8087**	Kaspersky AV
43	WHOIS	**631**	Internet Printing	**3222**	GLBP	**8118**	Privoxy
49	TACACS	**636**	LDAP over SSL	**3260**	iSCSI Target	**8200**	VMware Server
53	DNS	**639**	MSDP (PIM)	**3306**	MySQL	**8500**	Adobe ColdFusion
67-68	DHCP/BOOTP	**646**	LDP (MPLS)	**3389**	Terminal Server	**8767**	TeamSpeak
69	TFTP	**691**	MS Exchange	**3689**	iTunes	**8866**	Bagle.B
70	Gopher	**860**	iSCSI	**3690**	Subversion	**9100**	HP JetDirect
79	Finger	**873**	rsync	**3724**	World of Warcraft	**9101-9103**	Bacula
80	HTTP	**902**	VMware Server	**3784-3785**	Ventrilo	**9119**	MXit
88	Kerberos	**989-990**	FTP over SSL	**4333**	mSQL	**9800**	WebDAV
102	MS Exchange	**993**	IMAP4 over SSL	**4444**	Blaster	**9898**	Dabber
110	POP3	**995**	POP3 over SSL	**4664**	Google Desktop	**9988**	Rbot/Spybot
113	Ident	**1025**	Microsoft RPC	**4672**	eMule	**9999**	Urchin
119	NNTP (Usenet)	**1026-1029**	Windows Messenger	**4899**	Radmin	**10000**	Webmin
123	NTP	**1080**	SOCKS Proxy	**5000**	UPnP	**10000**	BackupExec
135	Microsoft RPC	**1080**	MyDoom	**5001**	Slingbox	**10113-10116**	NetIQ
137-139	NetBIOS	**1194**	OpenVPN	**5001**	iperf	**11371**	OpenPGP
143	IMAP4	**1214**	Kazaa	**5004-5005**	RTP	**12035-12036**	Second Life
161-162	SNMP	**1241**	Nessus	**5050**	Yahoo! Messenger	**12345**	NetBus
177	XDMCP	**1311**	Dell OpenManage	**5060**	SIP	**13720-13721**	NetBackup
179	BGP	**1337**	WASTE	**5190**	AIM/ICQ	**14567**	Battlefield

TYPES OF SERVERS

- Daemon server
  - Example: NTP server
- Superserver
- Stateless server
  - Example: Apache server
- Stateful server
- Object servers
- EJB servers

DAEMON SERVERS

- Servers run in background on Linux, respond to requests from local programs and remote users
- Daemons processes typically started at boot time
- One of three major Linux process types (interactive, batch, ***daemon***)
- Have single script under /etc/init.d defining how to start, restart, terminate, perform status checks, etc.
- **Example**: network time protocol (ntp) daemon
  - Listen locally on specific port (ntp is 123)
  - Routes local client traffic to the configured endpoint servers
  - University of Washington: time.u.washington.edu
  - Example "`ntpq –p`"
    - Queries local ntp daemon, routes traffic to configured server(s)
- Others: crond(task scheduler), ftpd, lpd(laser printing)…

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SUPERSERVER

- Linux (extended) internet service daemon inetd / xinetd
  - Used on Linux machines
  - One instance (single superserver) per machine
  - Superserver configures host to run multiple internet services
    - E.g. ftp, pop, telnet
  - PID 1, boots as first process
  - inetd daemon provides **common interface** for multiple services:
  - Perform service operations: restart, start, status, stop, etc.
  - "Start" forks a process to run specified "server"
  - Scripts under **/etc/init.d/** define server behavior
  - No longer installed / used by Ubuntu
  - Replaced by **upstart**, then **systemd:** start daemons concurrently
- Check ports you're listening on: How many daemons can you see?
  - `sudo netstat -tap | grep LISTEN`

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INTERRUPTING A SERVER

- Server design issue:
  - Active client/server communication is taking place over a port
  - How can the server / data transfer protocol support interruption?
- Consider transferring a 1 GB image, how do you pass a unrelated message in this stream?
  1. **Out-of-band** data: special messages sent in-stream to support interrupting the server (*TCP urgent data*)
     - Application protocol could be designed to accommodate OOB data
  2. Use a separate connection (different port) for admin control info
- Example: sftp secure file transfer protocol
  - Once a file transfer is started, can't be stopped easily
  - Must kill the client and/or server

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STATELESS SERVERS

- Data about state of clients is not stored
- Example: web application servers are typically stateless
  - Also function-as-a-service (FaaS) platforms
- Many servers maintain information on clients (e.g. log files)
- Loss of stateless data doesn't disrupt server availability
  - Loosing log files typically has minimal consequences
- **Soft state**: server maintains state on the client for a limited time (*to support sessions*)
- Soft state information expires and is deleted

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STATEFUL SERVERS

- Maintain persistent information about clients
- Information must be explicitly deleted by the server
- **Example:**
- Clients retrieve and store RW file copies from File server
- Server then tracks client file permissions and versions
  - Table tracks (client ID, filename) entries w/ metadata
- If server crashes data must be recovered
- Entire state before a crash must be restored
- Fault tolerance - *Ch. 8*

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STATEFUL SERVERS - 2

- Session state
  - State records sequence of operations by a single user
  - Maintained temporarily, not indefinitely by servers
  - Often retained for multi-tier client server applications
  - Minimal consequence if session state is lost
  - Clients may need to start over, reissue requests (*reinitialize sessions)*
- Permanent state
  - Customer information (address, etc.), software keys
- Client-side cookies
  - When servers don't maintain client state, clients can store state locally in "cookies"
  - Cookies are not executable, simply client-side data

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OBJECT SERVERS

- **OBJECTIVE:** Host objects and enable remote client access
- Do not provide a specific service
  - Do nothing if there are no objects to host
- Support adding/removing hosted objects
- Provide a home where objects live
- Objects, *themselves*, provide "services"
- Object parts
  - State data
  - Code (methods, etc.)
- **Transient object(s)**
  - Objects with limited lifetime (< server)
  - Created at first invocation, destroyed when no longer used (i.e. no clients remain "bound").
  - Disadvantage: initialization may be expensive
  - Alternative: preinitialize and retain objects on server at boot time

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OBJECT SERVERS - 2

- **Should object servers isolate memory for object instances?**
  - Share neither code nor data
  - May be necessary if objects couple data and implementation
- Object server threading design alternatives:
  - Single thread of control for object server
  - One thread for each object
  - Separate thread for every client request
- Threads created on demand ***vs.*** Server maintains pool of threads
- **What are the tradeoffs for creating server threads on demand vs. using a thread pool?**

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EJB – ENTERPRISE JAVA BEANS

- Enterprise JavaBeans (EJB) is architecture for transactional, component-based distributed computing
- Beans are components that run in EJB web container *(i.e. special web server that has nothing to do with Docker containers)*
- Developers just write beans (components)
- EJB architecture then automatically supports transaction support, security, remote object access, etc …
- 4 types of beans: stateless, stateful, entity, and message-driven beans
- **Key idea:** EJB provides "middleware" standard (framework) for implementing back-ends of enterprise applications
  - Simplifies distributed application development

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EJB - 2

- Architecture became less popular with advent of web services
- EJB web application containers integrate support for:
  - Transaction processing
  - Persistence
  - Concurrency
  - Event-driven programming
  - Asynchronous method invocation
  - Job scheduling
  - Naming and discovery services (JNDI)
  - Interprocess communication
  - Security
  - Software component deployment to an application server

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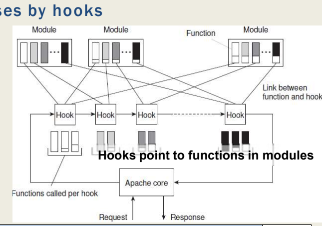
APACHE WEB SERVER

- Highly configurable, extensible, platform independent
- Supports TCP HTTP protocol communication
- Uses hooks – placeholders for group of functions
- Requests processed in phases by hooks
- Many hooks:
  - Translate a URL
  - Write info to log
  - Check client ID
  - Check access rights
- Hooks processed in order enforcing flow-of-control
- Functions in replaceable modules



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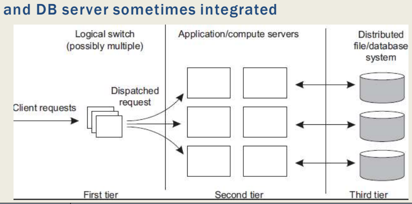
SERVER CLUSTERS

- Hosted across an LAN or WAN
- Collection of interconnected machines
- Can be organized in tiers:
  - Web server → app server → DB server
  - App and DB server sometimes integrated



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LAN REQUEST DISPATCHING

- Front end of three tier architecture (logical switch) provides distribution transparency – hides multiple servers
- Transport-layer switches: switch accepts TCP connection requests, ***hands off*** to a server
  - Example: hardware load balancer (F5 networks – Seattle)
  - HW Load balancer - OSI layers 4-7
- Network-address-translation (NAT) approach (***rewrite packets***):
  - All requests pass through switch
  - Switch sits in the middle of the client/server TCP connection
  - Maps (rewrites) source and destination addresses
- Connection hand-off approach (***not a proxy***)
  - **TCP Handoff**: switch hands off connection to a selected server
  - Key: connection is handed off. Server responds directly to client

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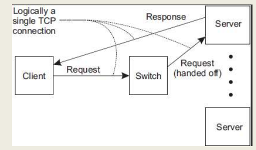
LAN REQUEST DISPATCHING - 2

- Hand-off is sticky. Session remains between client/server pair until closed (***not a proxy - dispatcher's job is done***)
- Which is the best server to handle the request?
- Switch plays important role in distributing requests
- Implements load balancing
- **Round-robin** – routes client requests to servers in a looping fashion
- **Transport-level** – route client requests based on TCP port number
- **Content-aware request distribution** – route requests based on inspecting data payload and determining which server node should process the request



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WIDE AREA CLUSTERS

- Deployed across the internet
- Leverage resource/infrastructure from Internet Service Providers (ISPs)
- Cloud computing simplifies building WAN clusters
- Resources from a single cloud provider can be combined to form a cluster
- **For deploying a cloud-based cluster (WAN), what are the implications of deploying nodes to:**
- (1) a single availability zone (e.g. us-east-1e)?
- (2) across multiple availability zones (us-east-1a, us-east-1e)?
- (3) across multiple Regions (e.g. us-east-1, us-west-2)?

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WAN REQUEST DISPATCHING

- Goal: minimize network latency using WANs (e.g. Internet)
- Send requests to nearby servers
- Request dispatcher: routes requests to nearby server
- **Example**: Domain Name System
  - Hierarchical decentralized naming system
- Linux: find your DNS servers:

```
# Find you device name of interest
nmcli dev
# Show device configuration
nmcli device show <device name>
```


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DNS LOOKUP

- First query local server(s) for address
- Typically there are (2) local DNS servers
  - One is backup
- Hostname may be cached at local DNS server
  - E.g. www.google.com
- If not found, local DNS server routes to other servers
- Routing based on components of the hostname
- DNS servers down the chain mask the client IP, and use the originating DNS server IP to identify a local host
- ***Weakness:*** *client may be far from DNS server used. Resolved hostname is close to DNS server, but not necessarily close to the client*

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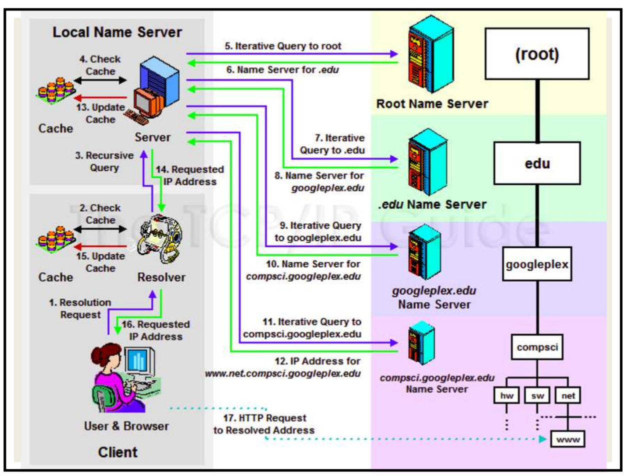

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DNS: LINUX COMMANDS

- `nslookup <ip addr / hostname>`
- Name server lookup – translates hostname or IP to the inverse
- `traceroute <ip addr / hostname>`
- Traces network path to destination
- By default, output is limited to 30 hops, can be increased

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DNS EXAMPLE – WAN DISPATCHING

- Ping www.google.com in WA from wireless network:
  - nslookup: 6 alternate addresses returned, choose (74.125.28.147)
  - Ping 74.125.28.147: Average RTT = **22.458 ms (11 attempts, 22 hops)**
- Ping www.google.com in VA (us-east-1) from EC2 instance:
  - nslookup: 1 address returned, choose 172.217.9.196
  - Ping 172.217.9.196: Average RTT = 1.278 ms (11 attempts, 13 hops)
- From VA EC2 instance, ping WA *www.google* server
- Ping 74.125.28.147: Average RTT 62.349ms (11 attempts, 27 hops)
- Pinging the WA-local server is ~60x slower from VA
- From local wireless network, ping VA us-east-1 google :
- Ping 172.217.9.196: Average RTT=81.637ms (11 attempts, 15 hops)

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DNS EXAMPLE – WAN DISPATCHING

- Ping www.google.com in WA from wireless network:
  - nslookup: 6 alternate addresses returned, choose (74.125.28.147)

Latency to ping "VA" google in WA: ~3.63x
WA laptop: local-google 22.458ms to VA-google 81.637ms

Latency to ping "WA" google in VA: ~48.7x
Virginia ec2 VM: local-google 1.278ms to WA-google 62.349!

- From local wireless network, ping VA us-east-1 google :
- Ping 172.217.9.196: Average RTT=81.637ms (11 attempts, 15 hops)

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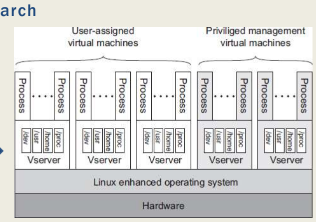
EXAMPLE: PLANETLAB

- Unstructured heterogeneous cluster of servers
- Similar to grid but organized as cluster (no grid middleware)
- Testbed established in 2002 for computer networking and distributed systems research
- Organizations share nodes in the cluster

Leverages Linux Vservers Early "containers" similar to Docker



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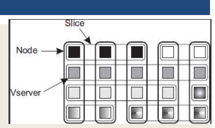
PLANETLAB - 2



- **Slices**: set of Vservers running across PlanetLab
- Acts as a virtual server cluster (similar to Amazon VPC)
- **Node manager**: manages Vservers running on a host
- **Slice creation service (SCS)**: To create virtual server clusters
- Clients must be **slice authorities** to create cluster
- **Rspec**: resource specification
  - Specifies resource requirements for a slice
- **Rcap**: resource capability
  - Specifies resource capabilities of nodes

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VSERVERS

- Early container based approach
- Vservers share a single operating system kernel
- Primary task is to support a group of processes
- Provides separation of name spaces
- Linux kernel maps process IDs: host OS → Vservers
- Each Vserver has its own set of libraries and file system
- Similar name separation as the "`chroot`" command
- Additional isolation provided to prevent unauthorized access among Vservers directory trees

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VSERVERS - 2

- **Advantages of Vservers (containers) vs. VMs:**
- Simpler resource allocation
- Possible to overbook resources by leveraging dynamic resource allocation - **Example: CPU or RAM** *(assignment 0, config 2)*
- VMs reserve a block of memory
- Containers can oversubscribe memory
  - Memory not formally reserved
  - Linux kernel shares memory among processes
  - Swap filesystem can use disk as extended RAM
- Memory sharing important for PlanetLab
  - Early nodes had limited memory (e.g. 4 GB)
- Vserver hogging most memory reset when out of swap space

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CH. 3.5: RESOURCE (CODE) MIGRATION

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RESOURCE MIGRATION

- To support on-the-fly reorganization of distributed systems, at times there is interest in resource migration
- Can consider various types of resource migration
  - Code migration: source code, libraries
  - Process migration: a running job/task
  - VM migration: an entire virtual server!

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CODE MIGRATION

- Distributed systems can support more than **passing data**
- Some situations call for **passing programs** (e.g. *code*)
- **Live migration** – moving code while it is executing
- **Portability** – transferring code (running or not) across heterogeneous systems:
  Mac OS X → Windows 10 → Linux
- Code migration enables ***flexibility*** of distributed systems
  - Topologies can be dynamically reconfigured on-the-fly

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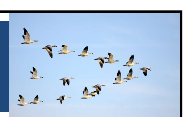
PROCESS MIGRATION



- Move an entire process from one node to another
- Motivation is always to address performance
- Process migration is slow, costly, and intricate
  - Need to pause, save intermediate state, move, resume
  - Consider application ***specific*** vs. ***agnostic*** approaches
- What would be:
  an **application agnostic** approach to migration?
  an **application specific** approach?
- What are advantages and disadvantages of each?

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PROCESS MIGRATION - 2

- **Move processes**:
  from heavily loaded → lightly loaded nodes
- When do we consider a node as heavily loaded?
  - Load average
  - CPU utilization
  - CPU queue length
- Which process(es) should be moved?
  - Must consider ***resource requirements*** for the task
- Where should process(es) be moved to?

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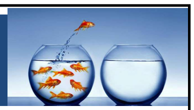
MOTIVATIONS FOR MIGRATION



- Can migrate **processes** or entire **virtual machines**
- **Goals:**
  - Off-loading machines: reduce load on oversubscribed servers
  - Loading machine: ensure machine has enough work to do
  - Minimize total hosts/servers in use to save energy/cost
- **VM migration:**
- Migrate complete VMs with apps to lightly loaded hosts
- Generally, VM migration is easier than process migration
- **Is VM migration application specific or agnostic?**

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LINUX CRIU

- Linux (CRIU) Checkpoint restore in userspace
- Linux tool: https://www.criu.org/
- Supports freezing a running application (or part of it) to create a checkpoint to persistent storage (e.g. disk) as a collection of files.
  - This means saving the state of RAM to disk
- Can use checkpoint files to restore and run the application from the point it was frozen at.
- Distinctive feature of CRIU is that it can be run in the user space (CPU user mode), rather than in kernel mode.
- CRIU can save a Docker container's state for migration elsewhere

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LOAD DISTRIBUTION ALGORITHMS

- Make decisions concerning allocation and redistribution of tasks across machines
- Provide resource management for compute intensive systems
- Often CPU centric
  - Algorithms should also account for other resources
  - Network capacity may be larger bottleneck that CPU capacity

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WHEN TO MIGRATE?

- Decisions to migrate code often based on qualitative reasoning or adhoc decisions vs. formal mathematical models
  - Difficult to formalize solutions due to heterogeneous composition and state of systems and networks
- **Is it better to migrate code or data?**
- **What factors should be considered?**
  - Size of code
  - Size of data
  - Available network transfer speed
  - Cost of data transfer
  - Processing power of nodes
  - Cost of processing
  - Are there security requirements for the data?

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APPROACHES TO CODE MIGRATION

- Traditional clients
  - Client interacts with server using specific protocol
  - Tight coupling of client->server limits system flexibility
  - Difficult to change protocol when there are ***many*** clients
- Dynamic web clients
  - Web browser downloads client code immediately before use
  - New versions can readily be distributed

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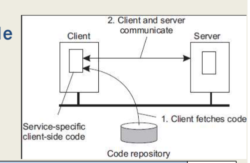
DYNAMIC WEB CLIENTS

- Advantages
  - Client code loaded in as necessary
  - Discarded when no longer needed
  - Can easily change the client/server protocol
- Disadvantages
  - Security: we have to trust the code
  - Downloading client requires network bandwidth & time



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CODE MIGRATION

- Sender-initiated: (upload the code)… e.g. Github
- Receiver-initiated: (download the code)… e.g. web browser
- **Remote cloning**
  - Produce a copy of the process on another machine while parent runs

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CODE MIGRATION - 2

- What is migrated?
  - ***Code*** segment
  - ***Resource*** segment (device info)
  - ***Execution*** segment (process info: data, statem stack, PC)
- **Weak mobility**
  - Only ***code*** segment, no state
  - Code always restarts
- **Strong mobility**
  - ***Code*** + ***execution*** segment
  - Process stopped, state saved, moved, resumed
  - Represents true ***process migration***

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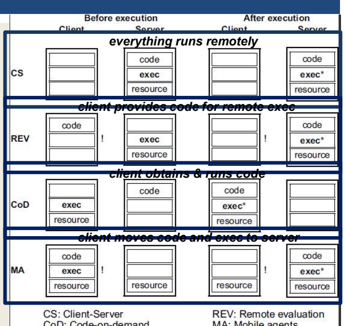
CODE MOBILITY TYPES

- * indicates what is modified
- CS: Client-Server
- REV: Remote Evaluation
- CoD: Code-on-demand
- MA: Mobile agents
- Where does state get modified?
- State is stored in **exec**



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MIGRATION OF HETEROGENEOUS SYSTEMS

- Assumption: code will always work at new node
- Invalid if node architecture is different (*heterogeneous*)
- What approaches are available to migrate code across heterogeneous systems?
- Intermediate code
  - 1970s Pascal: generate machine-independent intermediate code
  - Programs could then run anywhere
  - **Today:** web languages: Javascript, Java
- VM Migration

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VIRTUAL MACHINE MIGRATION

- Four approaches:

1. **PRECOPY**: Push all memory pages to new machine *(slow)*, resend modified pages later, transfer control
2. **STOP-AND-COPY**: Stop the VM, migrate memory pages, start new VM
3. **ON DEMAND**: Start new VM, copy memory as needed
4. **HYBRID**: PRECOPY followed by brief STOP-AND-COPY

- **What are some advantages and disadvantages of 1-4?**

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1. **PRECOPY**: Push all memory pages to new machine *(slow)*, resend modified pages later, transfer control
2. **STOP-AND-COPY**: Stop the VM, migrate memory pages, start new VM
3. **ON DEMAND**: Start new VM, copy memory pages as needed
4. **HYBRID**: PRECOPY and followed by brief STOP-AND-COPY

- **What are some advantages and disadvantages of 1-4?**
  - 1/3: no loss of service
  - 4: fast transfer, minimal loss of service
  - 2: fastest data transfer
  - 3: new VM immediately available
  - 1: must track modified pages during full page copy
  - 2: longest downtime - unacceptable for live services
  - 3: prolonged, slow, migration
  - 3: original VM must stay online for quite a while
  - 1/3: network load while original VM still in service

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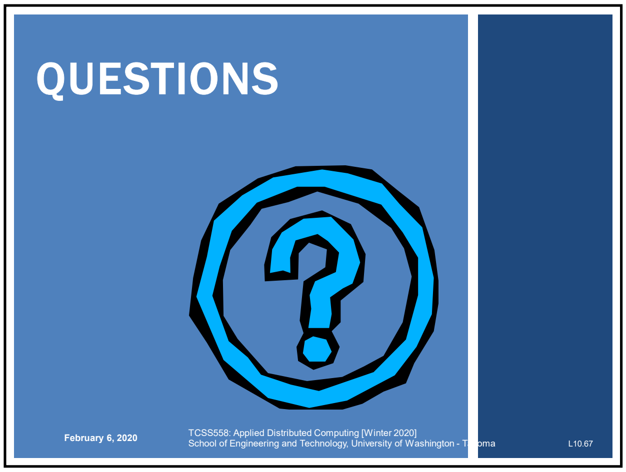
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