Distributed Systems

01. Introduction

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What can we do now that we could not do before?

~30 years ago

- 1986: The Internet is 17 years old

Technology advances

Networking

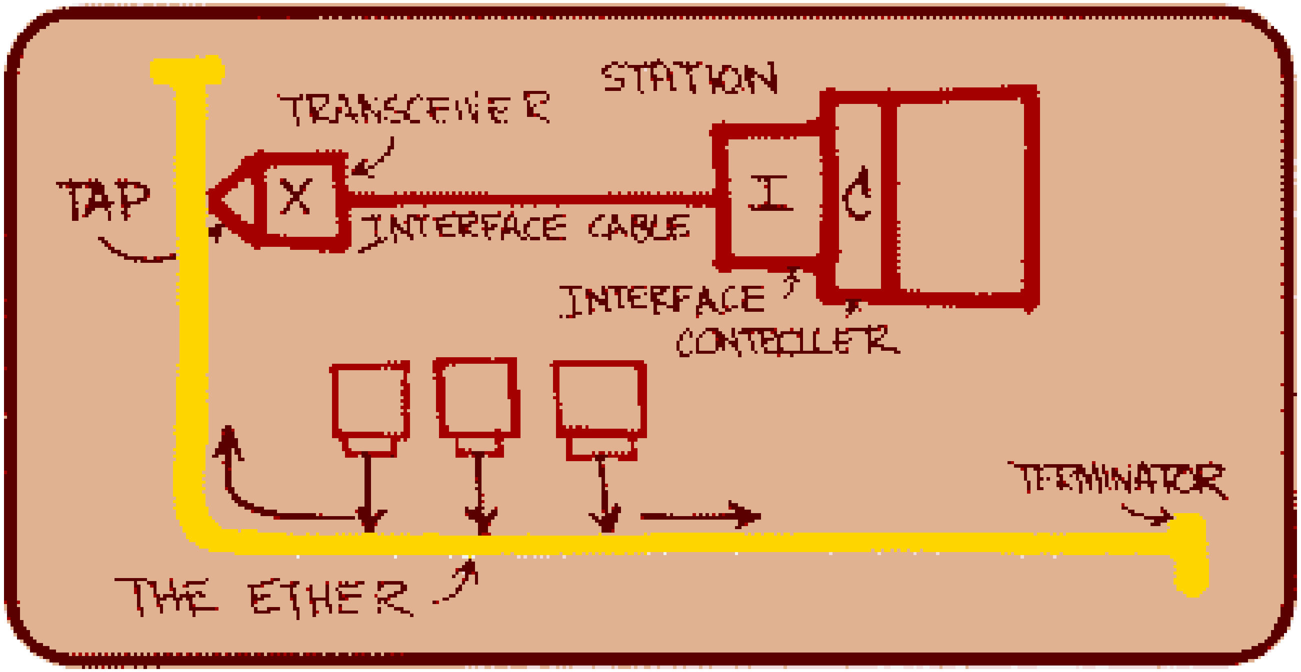
Processors

Memory

Storage

Protocols

Networking: Ethernet – 1973, 1976



June 1976: Robert Metcalfe presents the concept of *Ethernet* at the National Computer Conference

1980: Ethernet introduced as de facto standard (DEC, Intel, Xerox)

Network architecture

100 – >10,000x faster

LAN speeds

- Original Ethernet: 2.94 Mbps
- **1985**: thick Ethernet: 10 Mbps – 1 Mbps with twisted pair networking
- **1991**: 10BaseT - twisted pair: 10 Mbps – Switched networking: **scalable bandwidth**
- **1995**: 100 Mbps Ethernet
- **1998**: 1 Gbps (Gigabit) Ethernet
- **2001**: 10 Gbps introduced
- **2005-now**: 40/100 Gbps

+ Wireless LAN

  1999: 802.11b (wireless Ethernet) standardized

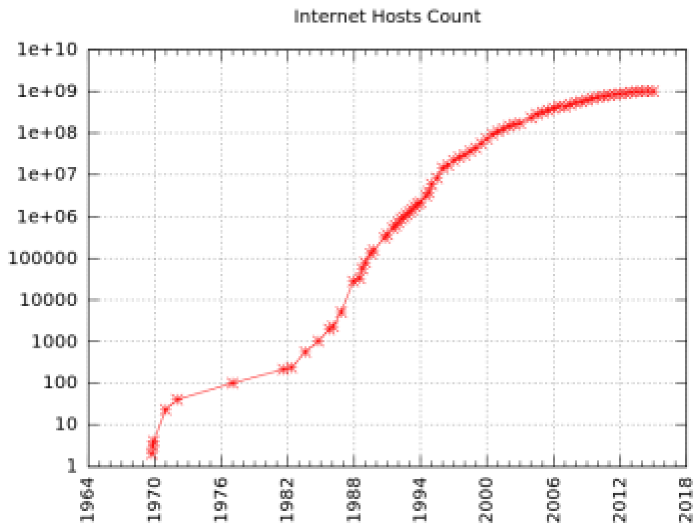
  2014: 802.11ac = 8×866.7 Mbps = 7 Gbps

+ Personal Area Networks: Bluetooth, ZigBee, Z-Wave

Network Connectivity

Then:

- Large companies and universities on Internet
- Gateways between other networks
- Consumers used dial-up bulletin boards
- 1985: 1,961 hosts on the Internet



Now:

- One Internet (mostly)
- Over a billion hosts
- Widespread connectivity
- High-speed WAN connectivity: >50 Mbps … 1 Gbps
- Switched LANs
- Wireless networking

https://www.isc.org/network/survey/

Metcalfe's Law

The value of a telecommunications network is proportional to the square of the number of connected users of the system.

This makes networking interesting to us!

Computing Power

Computers got…

- Smaller
- Cheaper
- Power efficient
- Faster

Microprocessors became technology leaders

Computing Power (Intel Processors)

1985-now:

- 714x smaller transistors
- >7000x more transistors
- >120x faster clock

We can no longer make CPUs much faster.

How do we get increased performance? *More cores.*

→Parallel system on a chip

8080 (1977)
2 MHz
6K transistors @ 10µm

386DX (1985)
33 MHz
275K transistors @ 1.5µm

Pentium Pro (1995)
200 MHz
5.5M transistors @ 500nm

Pentium D (2005)
2.6 – 3.7 GHz
2 cores
169M transistors @ 90nm

Xeon Haswell-E5 (2015)
2.3 GHz
18 cores, 2.5 MB cache/core
5.6M transistors @ 22nm

I7-6700K Skylake (2015)
4.0 GHz
4 cores, 8 MB shared cache
~1.3M transistors @ 14nm

GPUs scaled too: 2016 – Quadro P6000: 12 billion transistors, 3,840 CUDA cores

Network Content: Music

Example: 9,839 songs

- 49 GB
- Average song size: 5.2 MB

Today

- Streaming (Pandora/Spotify): 96-320 kbps
- Download time per song @100 Mbps: ~ 0.4 seconds
- Storage cost for the collection: ~ $1.60 ($120 for a 4 TB drive)

~30 years ago (1985)

- Streaming not practical
- Download time per song, V90 modem @44 Kbps: 15 minutes
- Storage cost: $511,640 (40 MB at $400 – over 1,279 drives!)

Network Content: Video

Today

- Netflix streaming 4K video @ 15.6 Mbps (HEVC/h.265 codec)
- YouTube: stores ~76 PB (76×10^{15}) per year

~30 years ago (1985)

- Video streaming not feasible

Protocols

Many have been devloped →

These are the APIs for network interaction

Faster CPU →

more time for protocol processing

- ECC, TCP checksums, parsing
- Image, audio compression feasible

Faster network →

→ support bigger (and bloated) protocols

- e.g., SOAP/XML, JSON – human-readable, explicit typing

Building and classifying parallel and distributed systems

Flynn's Taxonomy (1966)

Number of instruction streams and number of data streams

SISD

– traditional uniprocessor system

SIMD

– array (vector) processor
– Examples:
  - GPUs – Graphical Processing Units for video
  - AVX: Intel's Advanced Vector Extensions
  - GPGPU (General Purpose GPU): AMD/ATI, NVIDIA

MISD

– Generally not used and doesn't make sense
– Sometimes (rarely!) applied to classifying fault-tolerant redundant systems

MIMD

– multiple computers, each with:
  - program counter, program (instructions), data
– **parallel and distributed systems**

Subclassifying MIMD

memory

- shared memory systems: <u>multiprocessors</u>
- no shared memory: networks of computers, <u>multicomputers</u>

interconnect

- bus
- switch

delay/bandwidth

- tightly coupled systems
- loosely coupled systems

Parallel Systems: Multiprocessors

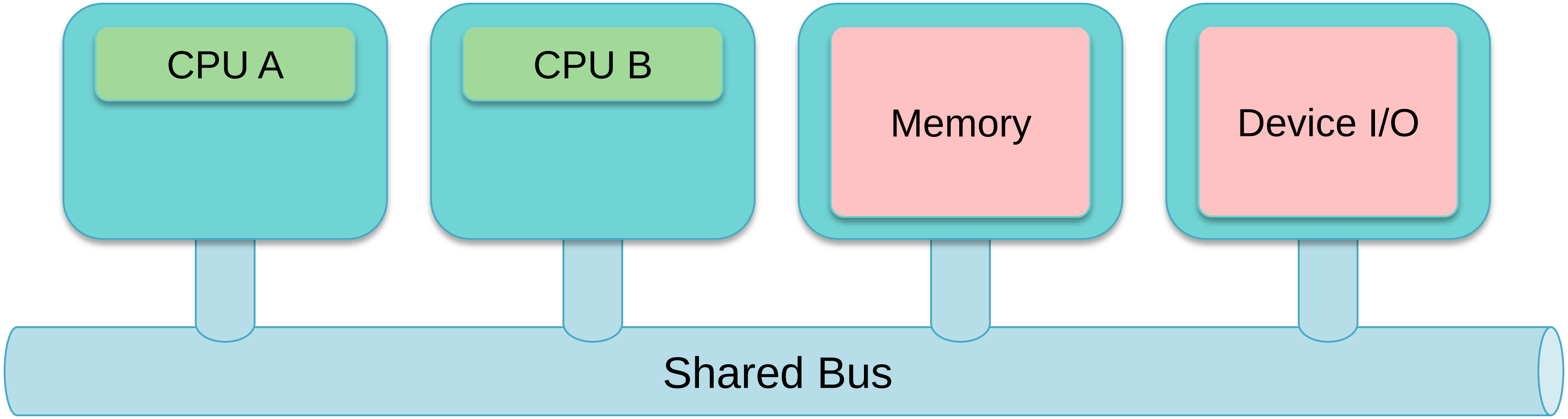
- Shared memory
- Shared clock
- All-or-nothing failure

Bus-based multiprocessors

SMP: Symmetric Multi-Processing

All CPUs connected to one bus (backplane)

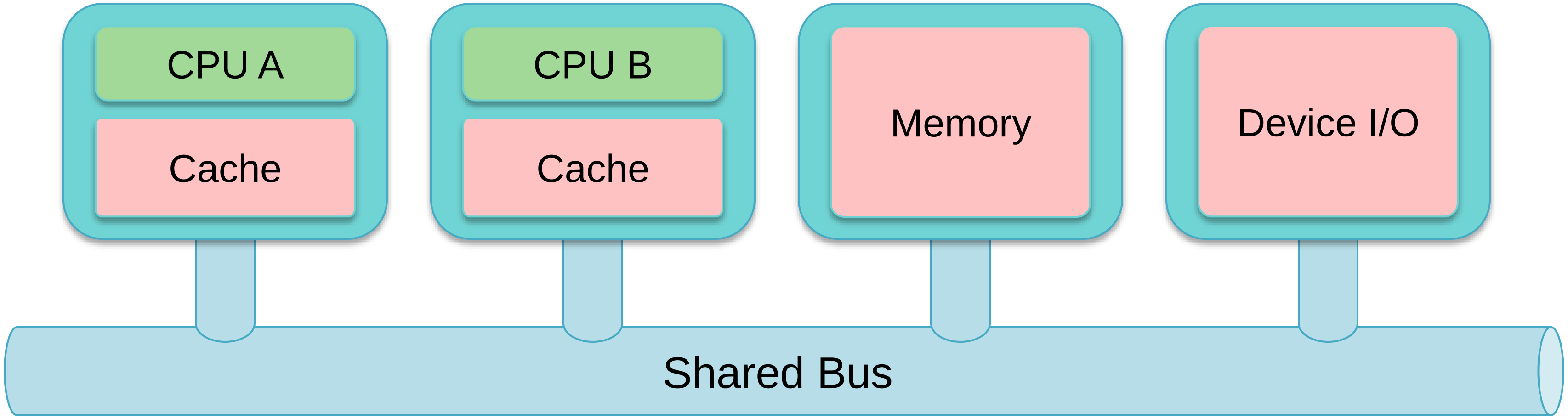
Memory and peripherals are accessed via shared bus. System looks the same from any processor.



The bus becomes a point of congestion … limits performance

Bus-based multiprocessors + cache

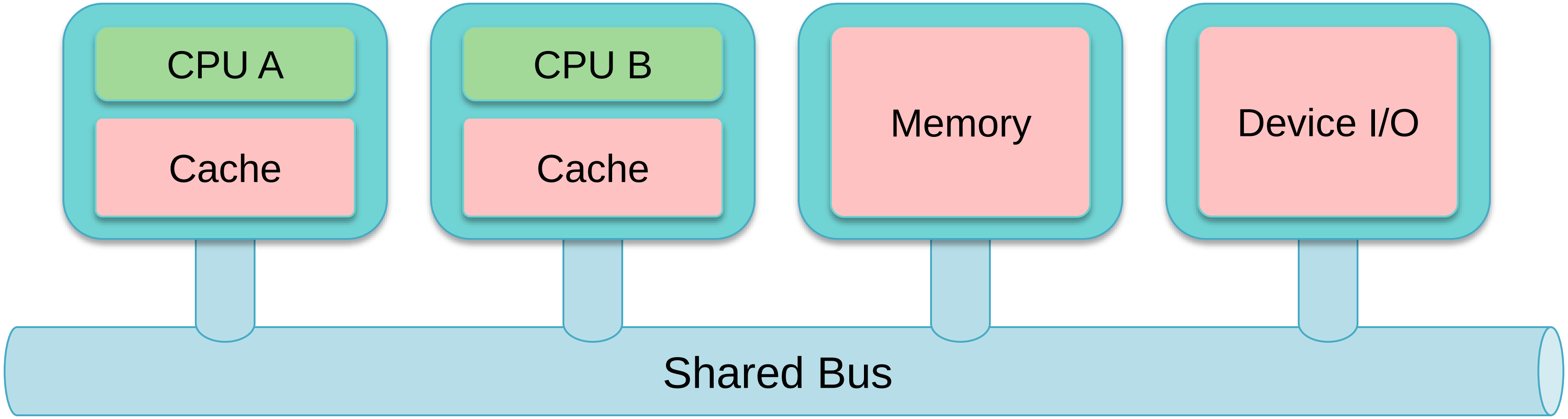
- The cache: great idea to deal with bus overload & memory contention
  – Cache = low-latency memory that is local to a processor
- CPU reads/writes cache memory
  – Access main memory only on cache miss



Memory coherence is now a problem

Write-through cache

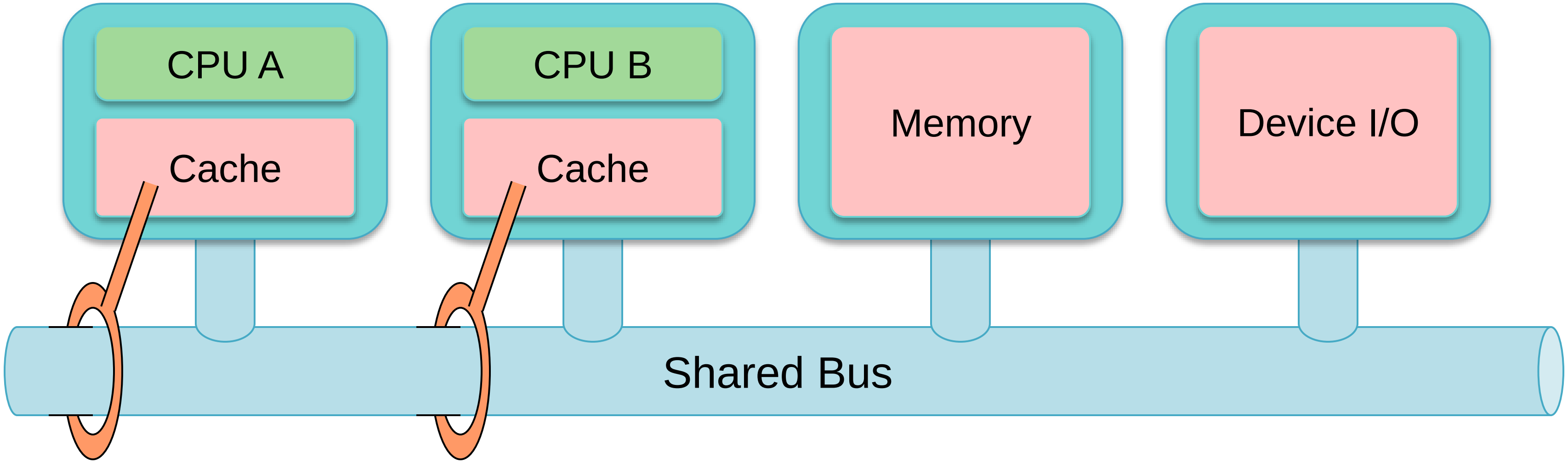
- Try to fix coherence problem with a write-through cache
  – Updates to cache are propagated to main memory
- But other caches may still have stale data!



Memory coherence is now a problem

Snoopy cache

- Add snooping logic to each cache controller
- Modified data is written to main memory
- Each cache snoops on bus traffic to see if its cached data is modified



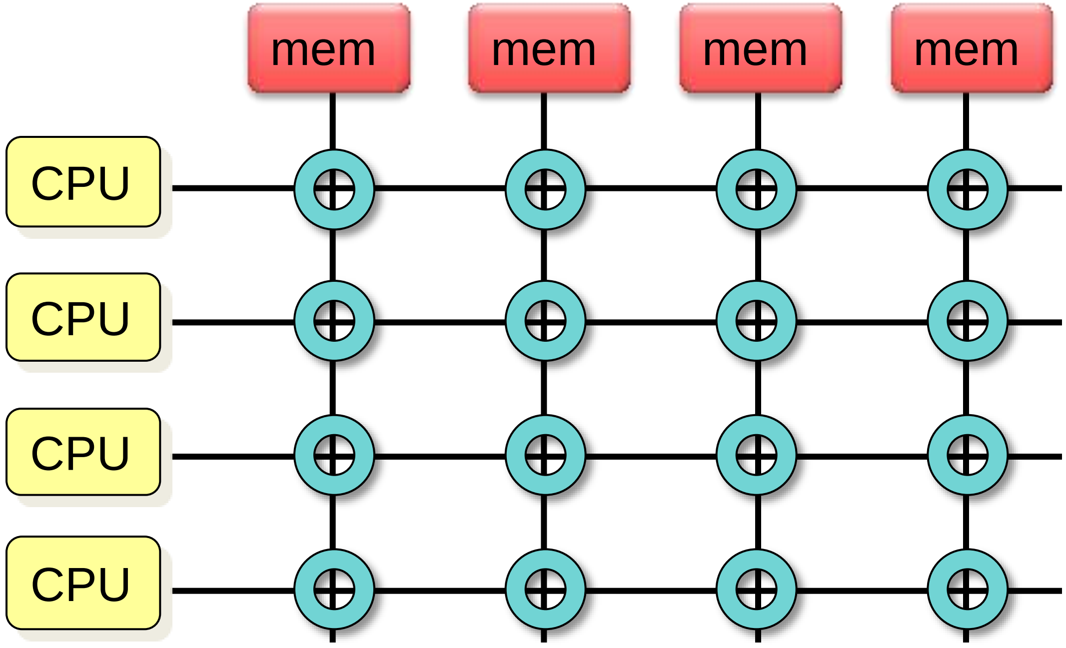
Memory coherence is now a problem

Switched multiprocessors

- Bus-based architecture does not scale linearly to large number of CPUs (e.g., beyond 8)

Switched multiprocessors

Divide memory into groups and connect chunks of memory to the processors with a **crossbar switch**



n^2 crosspoint switches – expensive switching fabric

We still want to cache at each CPU – but we cannot snoop!

NUMA

- Hierarchical Memory System
- All CPUs see the same address space
- Each CPU has local connectivity to a region of memory
  - fast access
- Access to other regions of memory – slower
- Placement of code and data becomes challenging
  - Operating system has to be aware of memory allocation and CPU scheduling

NUMA

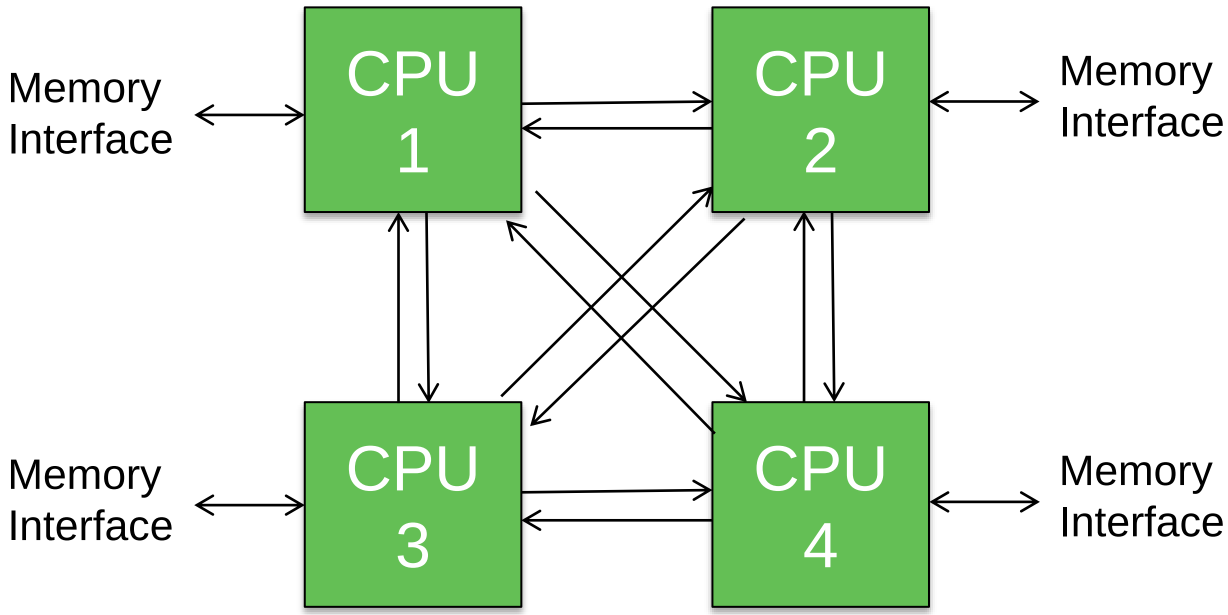
- SGI Origin's ccNUMA
- AMD64 Opteron
  - Each CPU gets a bank of DDR memory
  - Inter-processor communications are sent over a HyperTransport link
- Intel
  - Integrated Memory Controller (IMC): fast channel to local memory
  - QuickPath Interconnect: point-to-point interconnect among processors
- Linux ≥2.5 kernel, Windows ≥7
  - Multiple run queues
  - Structures for determining layout of memory and processors

Cache Coherence With Switched CPUs

Intel Example

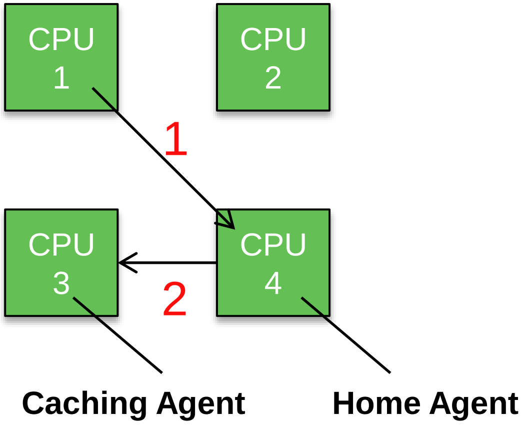
Home Snoop: *Home-based consistency protocol*

- Each CPU is responsible for a region of memory
- It is the "home agent" for that memory
  - Each home agent maintains a directory (table) that keeps track of who has the latest version



Cache Coherence With Switched CPUs

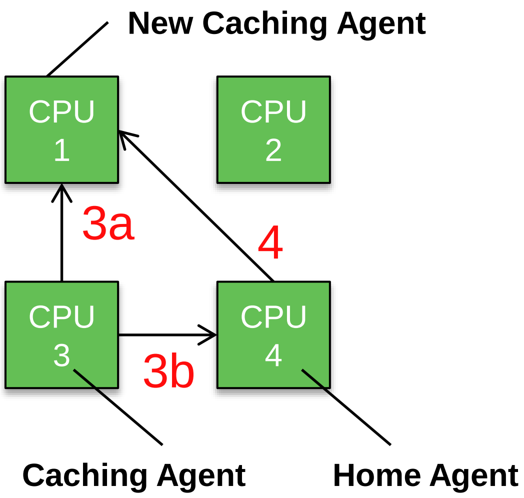
1. CPU sends request to home agent
2. Home agent requests status from the CPU that may have a cached copy (caching agent)



Cache Coherence With Switched CPUs

3. (a) Caching agent sends data update to new caching agent
   (b) Caching agent sends status update to home agent

4. Home agent resolves any conflicts & completes transaction

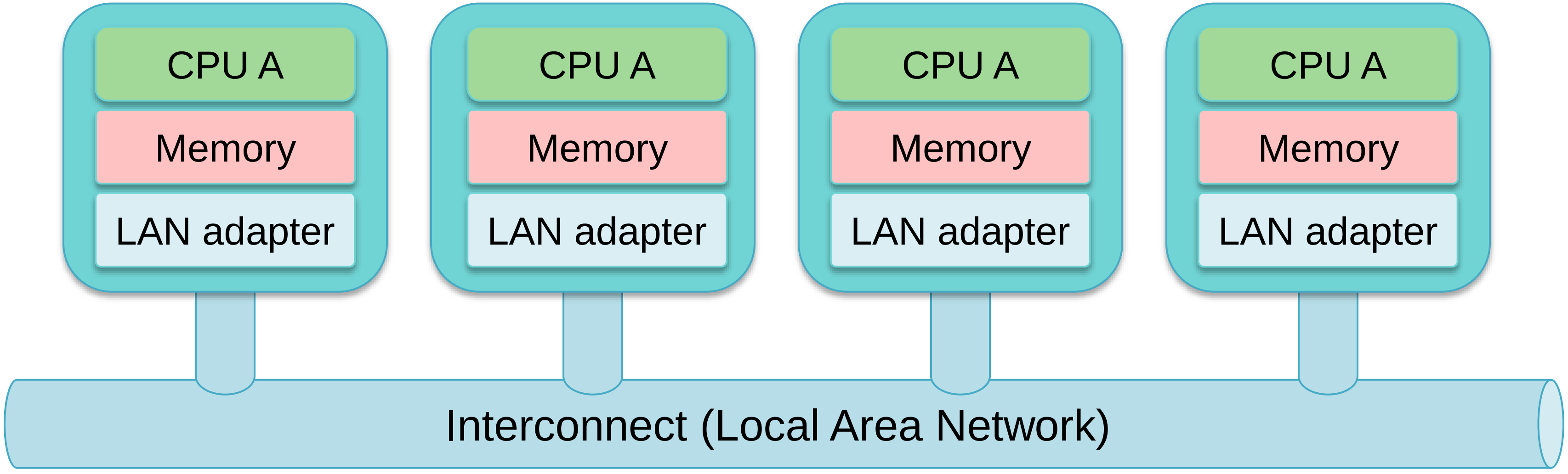


Networks of computers

- Eventually, other bottlenecks occur
  - Network, disk
- We want to scale beyond multiprocessors
  - Multicomputers
- No shared memory, no shared clock
- Communication mechanism needed
  - Traffic much lower than memory access
  - Network

Bus-based multicomputers

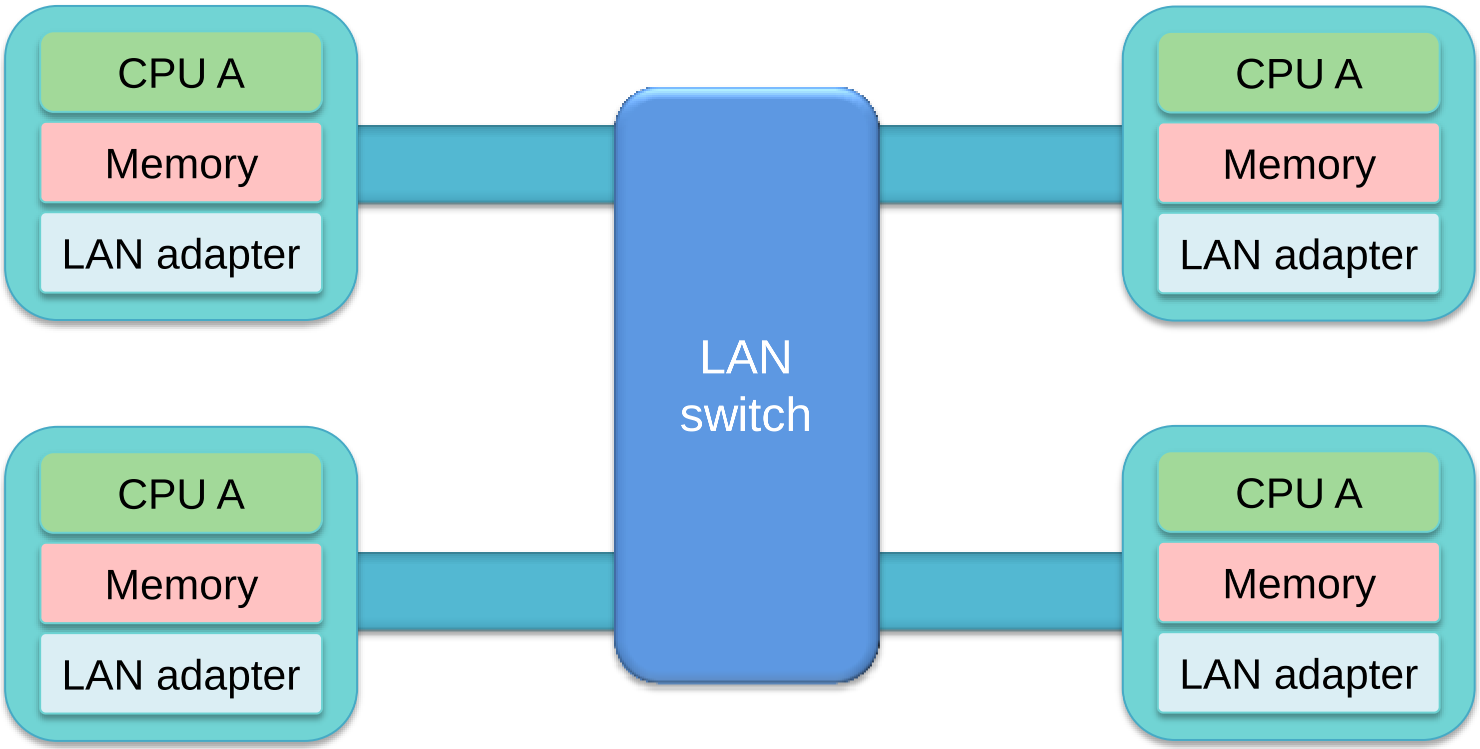
Collection of workstations on a LAN



A shared bus-based interconnect gives us the option of *snooping* on network traffic

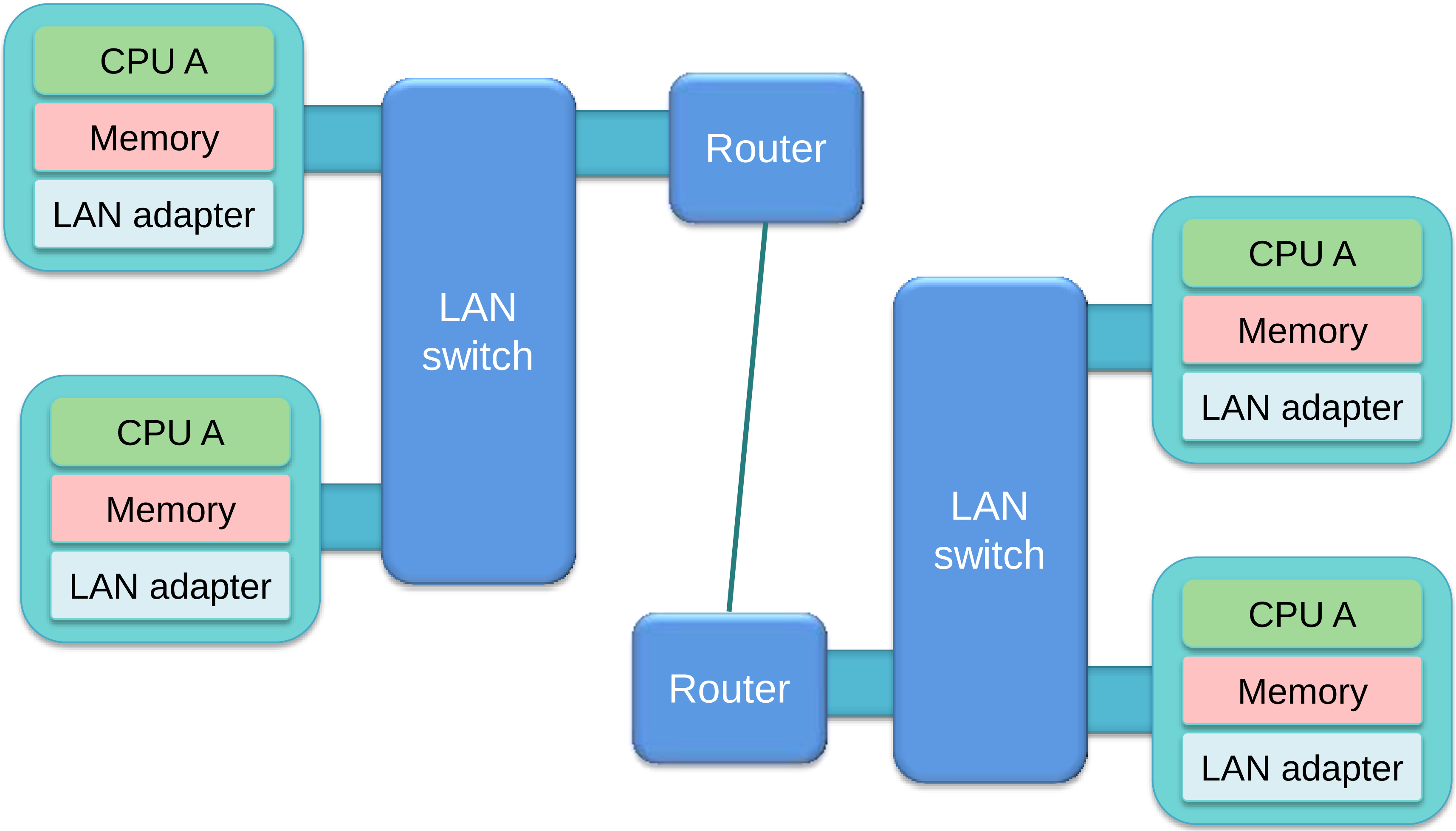
Switched multicomputers

Collection of workstations on a LAN



A switched interconnect does not allow snooping

Wide Area Distribution



What is a Distributed System?

A collection of independent, autonomous hosts connected through a communication network.

– No shared memory (must use the network)
– No shared clock

Single System Image

Collection of independent computers that appears as a single system to the user(s)

- Independent = autonomous
- Single system: user not aware of distribution

You know you have a distributed system when the crash of a computer you've never heard of stops you from getting any work done.

– Leslie Lamport

Why build distributed systems?

How can you get massive performance?

- Multiprocessor systems don't scale

- Example: movie rendering
  - Disney's Cars 2 required 11.5 hours to render each frame (average) – some took 90 hours to render!
    - 12,500 cores on Dell render blades
  - Monsters University required an average of 29 hours per frame
    - Total time: over 100 million CPU hours
    - 3,000 to over 5,000 AMD processors; 10 Gbps and 1 Gbps networks

- Google
  - Over 40,000 search queries per second on average
  - Index >50 billion web pages
  - Uses hundreds of thousands of servers to do this

Google

- In 1999, it took Google one month to crawl and build an index of about 50 million pages
  In 2012, the same task was accomplished in less than one minute.

- 16% to 20% of queries that get asked every day have never been asked before

- Every query has to travel on average 1,500 miles to a data center and back to return the answer to the user

- A single Google query uses 1,000 computers in 0.2 seconds to retrieve an answer

Source: http://www.internetlivestats.com/google-search-statistics/

Why build distributed systems?

- Performance ratio
  - Scaling multiprocessors may not be possible or cost effective
- Distributing applications may make sense
  - ATMs, graphics, remote monitoring
- Interactive communication & entertainment
  - Work, play, keep in touch:
    messaging, photo/video sharing, gaming, telephony
- Remote content
  - Web browsing, music & video downloads, IPTV, file servers
- Mobility
- Increased reliability
- Incremental growth

Design goals: Transparency

High level: hide distribution from users

Low level: hide distribution from software

- Location transparency
  Users don't care where resources are
- Migration transparency
  Resources move at will
- Replication transparency
  Users cannot tell whether there are copies of resources
- Concurrency transparency
  Users share resources transparently
- Parallelism transparency
  Operations take place in parallel without user's knowledge

Design challenges

Reliability

- **Availability**: fraction of time system is usable
  - Achieve with redundancy
  - But consistency is an issue!
- **Reliability**: data must not get lost
  - Includes security

Scalability

- Distributable vs. centralized algorithms
- Can we take advantage of having lots of computers?

Performance

- Network latency, replication, consensus

Programming

- Languages & APIs

Network

- Disconnect, latency, loss of data

Security

- Important but we want convenient access as well

Main themes in distributed systems

- Scalability
  - Things are easy on a small scale
  - But on a large scale
    - Geographic latency (multiple data centers), administration, dealing with many thousands of systems
- Latency & asynchronous processes
  - Processes run asynchronously: concurrency
  - Some messages may take longer to arrive than others
- Availability & fault tolerance
  - Fraction of time that the system is functioning
  - Dead systems, dead processes, dead communication links, lost messages
- Security
  - Authentication, authorization, encryption

Key approaches in distributed systems

- Divide & conquer
  - Break up data sets and have each system work on a small part
  - Merging results is usually efficient
- Replication
  - For high availability, caching, and sharing data
  - Challenge: keep replicas consistent even if systems go down and come up
- Quorum/consensus
  - Enable a group to reach agreement

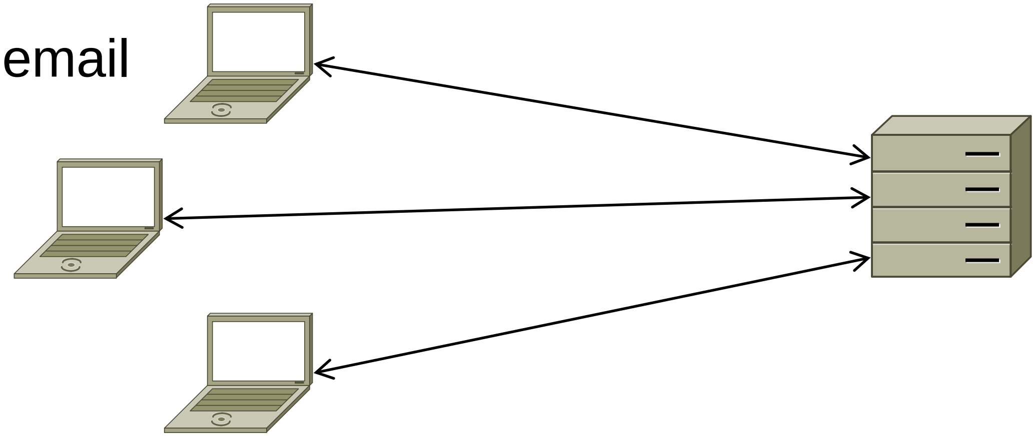
Service Models (Application Architectures)

Centralized model

- No networking
- Traditional time-sharing system
- Single workstation/PC or direct connection of multiple terminals to a computer
- One or several CPUs
- Not easily scalable
- Limiting factor: number of CPUs in system
  – Contention for same resources (memory, network, devices)

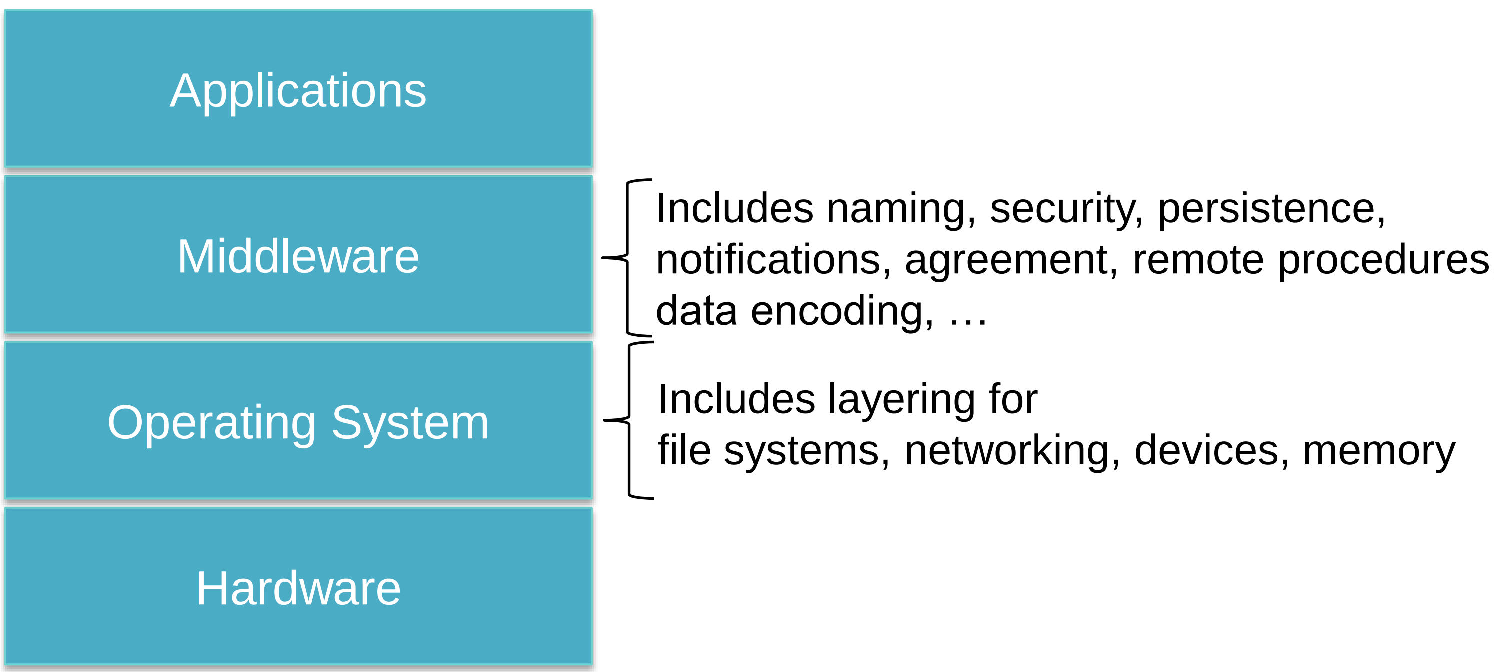
Client-Server model

- Clients send requests to servers
- A server is a system that runs a service
- The server is always on and processes requests from clients
- Clients do not communicate with other clients
- Examples
  – FTP, web, email



Layered architectures

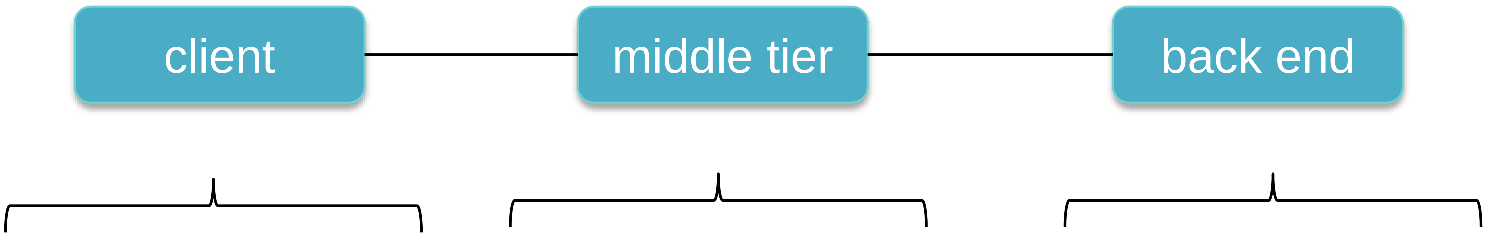
- Break functionality into multiple layers
- Each layer handles a specific abstraction
  - Hides implementation details and specifics of hardware, OS, network abstractions, data encoding, …



Tiered architectures

- Tiered (multi-tier) architectures
  - distributed systems analogy to a layered architecture
- Each tier (layer)
  - Runs as a network service
  - Is accessed by surrounding layers
- The "classic" client-server architecture is a two-tier model
  - Clients: typically responsible for user interaction
  - Servers: responsible for back-end services (data access, printing, …)

Multi-tier example

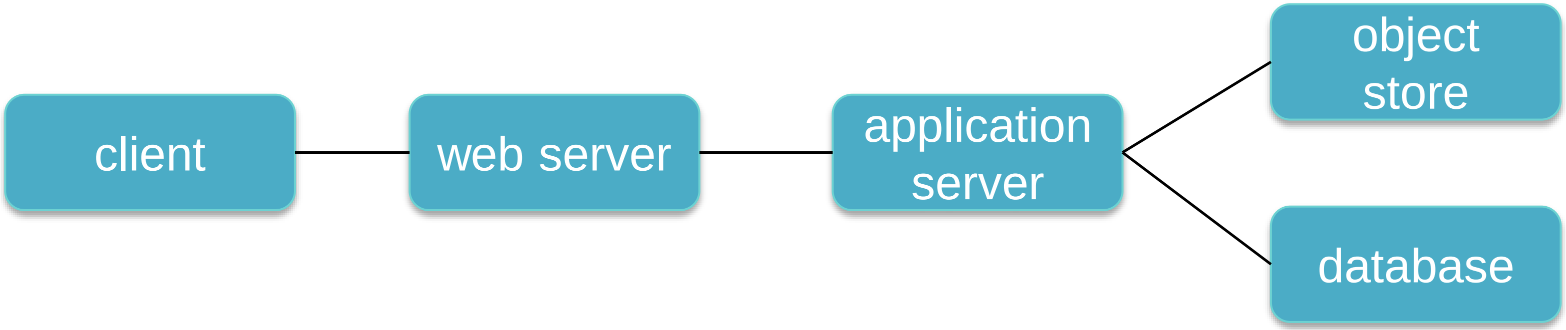


User interface
Data presentation
& validation

- Queuing requests
- Coordinating a transaction among multiple servers
- Managing connections
- Formatting/converting data

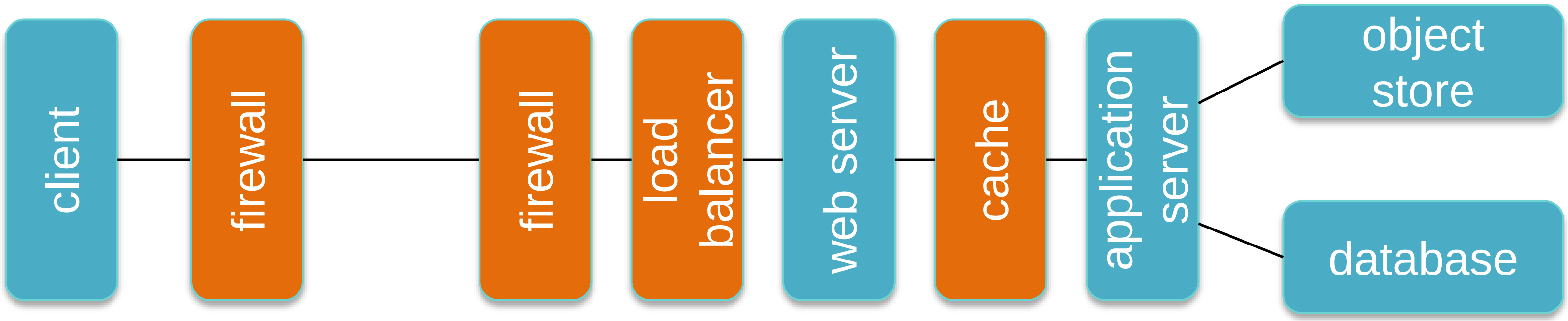
- Database system
- Legacy software

Multi-tier example



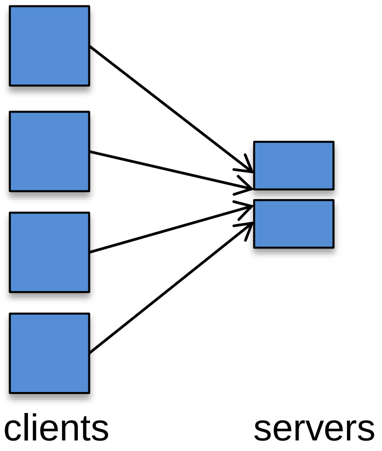
Multi-tier example

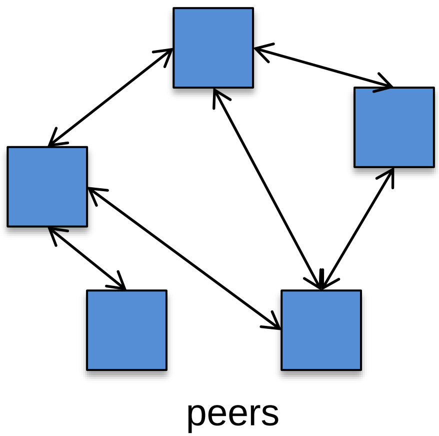
Some tiers may be transparent to the application



Peer-to-Peer (P2P) Model

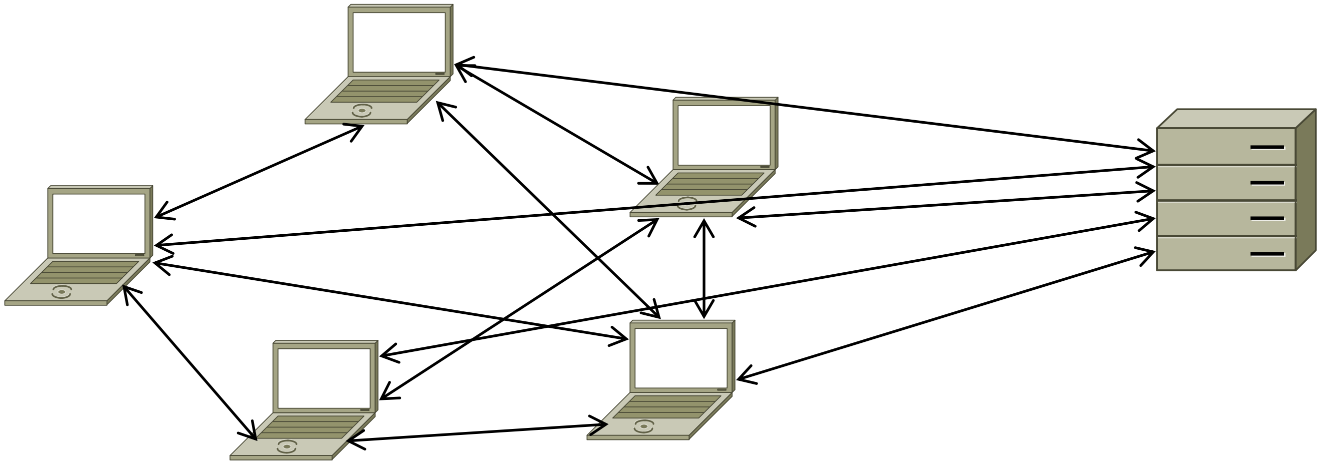
- No reliance on servers
- Machines (peers) communicate with each other
- Goals
  - Robustness
    - Expect that some systems may be down
  - Self-scalability: the system can handle greater workloads as more peers are added
- Examples
  - BitTorrent, Skype





Hybrid model

- Many peer-to-peer architectures still rely on a server
  - Look up, track users
  - Track content
  - Coordinate access
- But traffic-intensive workloads are delegated to peers



Processor pool model

- Collection of CPUs that can be assigned processes on demand
- Render farms

Cloud Computing

Resources are provided as a network (Internet) service

- Software as a Service (SaaS)
  Remotely hosted software
  - *Salesforce.com, Google Apps, Microsoft Office 365*
- Infrastructure as a Service (IaaS)
  Compute + storage + networking
  - *Microsoft Azure, Google Compute Engine, Amazon Web Services*
- Platform as a Service (PaaS)
  Deploy & run web applications without setting up the infrastructure
  - *Google App Engine, AWS Elastic Beanstalk*
- Storage
  Remote file storage
  - *Dropbox, Box, Google Drive, OneDrive, …*

The end