DISTRIBUTED SYSTEMS
CS6421
DISTRIBUTED ARCHITECTURE

Prof. Roozbeh Haghnazar

Slides Credit:

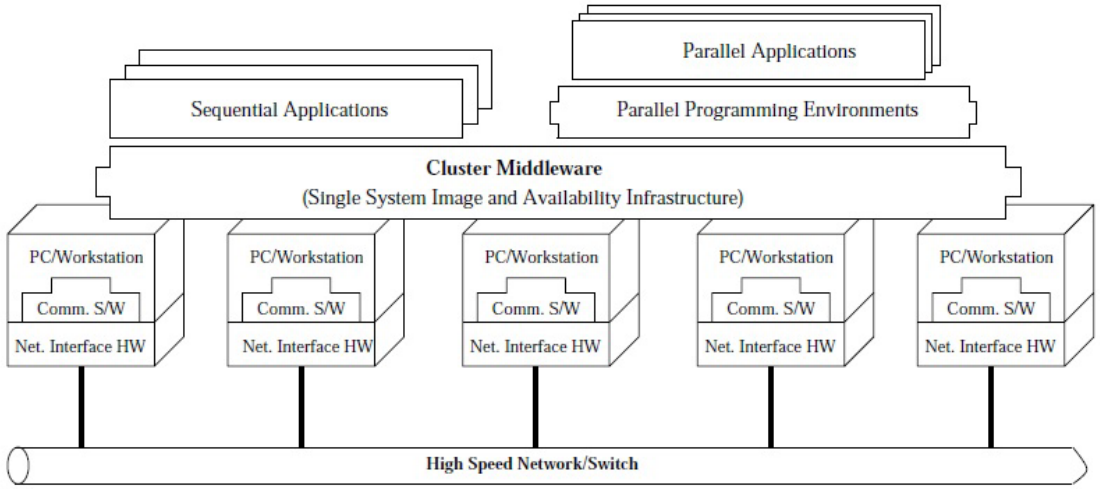
Prof. Tim Wood and Prof. Roozbeh Haghnazar

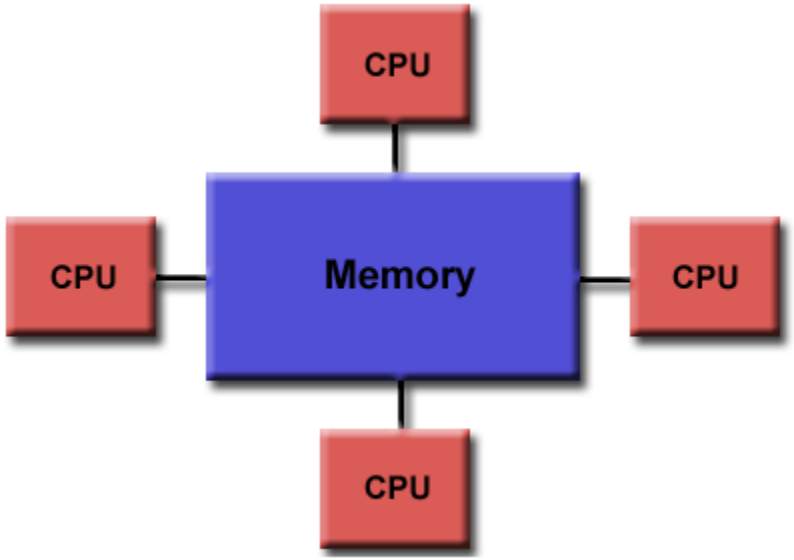
Includes material adapted from Van Steen and Tanenbaum's Distributed Systems book

TYPES OF DISTRIBUTED SYSTEMS

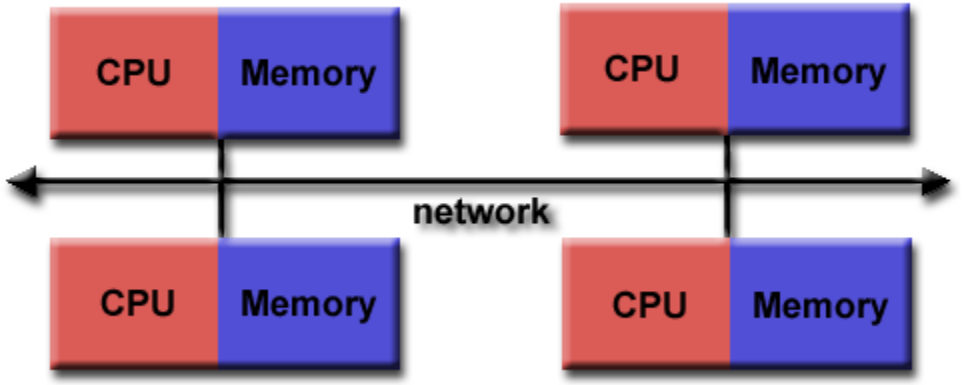
- Distributed Computing Systems
  - Clusters
  - Grids
- Distributed Information Systems
  - Transaction Processing Systems
  - Enterprise Application Integration
- Distributed Embedded Systems
  - Home systems
  - Health care systems
  - Sensor networks

CLUSTER COMPUTING





Shared Memory: Uniform Memory Access Obtained from www.computing.llnl.gov



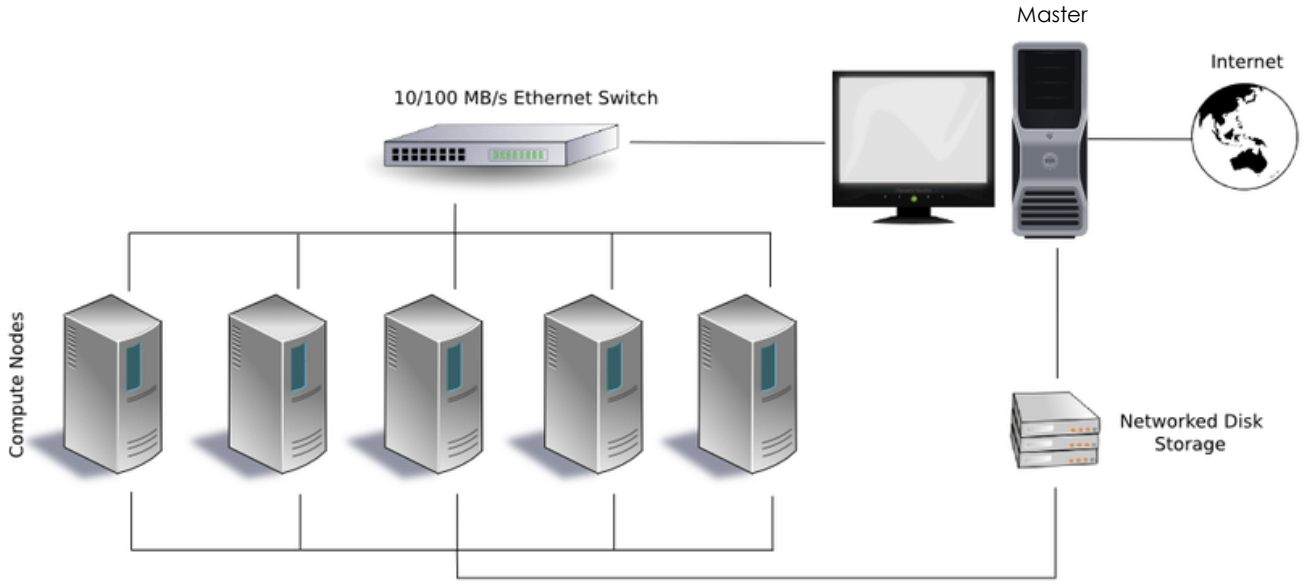
Distributed Memory System Obtained from www.computing.llnl.gov

CLUSTERS CLASSIFICATIONS

- High Performance
- Expandability and Scalability
- High Throughput
- High Availability

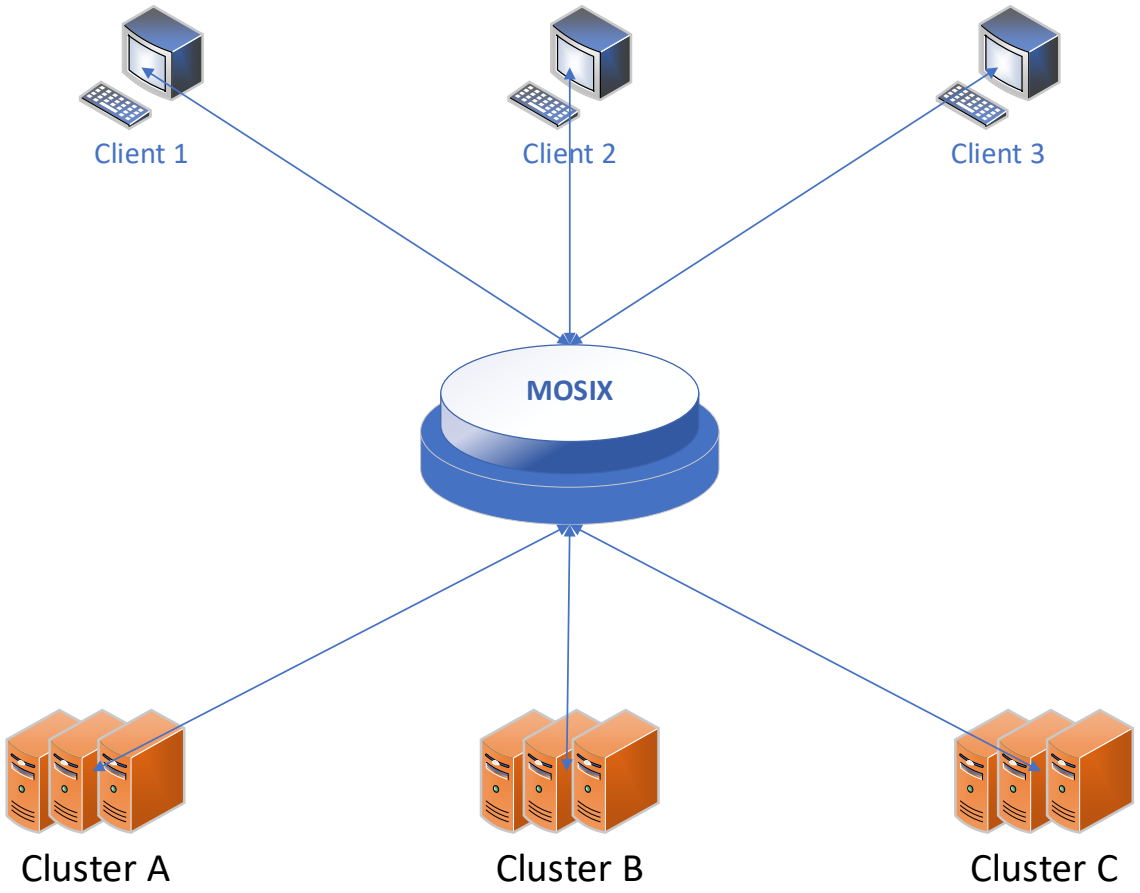
CLUSTERS – BEOWULF MODEL

- Master-slave paradigm
  - One processor is the master; allocates tasks to other processors, maintains batch queue of submitted jobs, handles interface to users
  - Master has libraries to handle message-based communication or other features (the middleware).
- Proper for parallel programs



CLUSTERS – MOSIX MODEL

- Provides a **symmetric**, rather than **hierarchical** paradigm
  - Single system image simplifies deployment
  - Processes can migrate between nodes dynamically
- "Operating-system-like"; looks & feels like a single computer with multiple processors
  - Provides resource discovery and and automatic workload distribution among clusters



GRID COMPUTING SYSTEMS

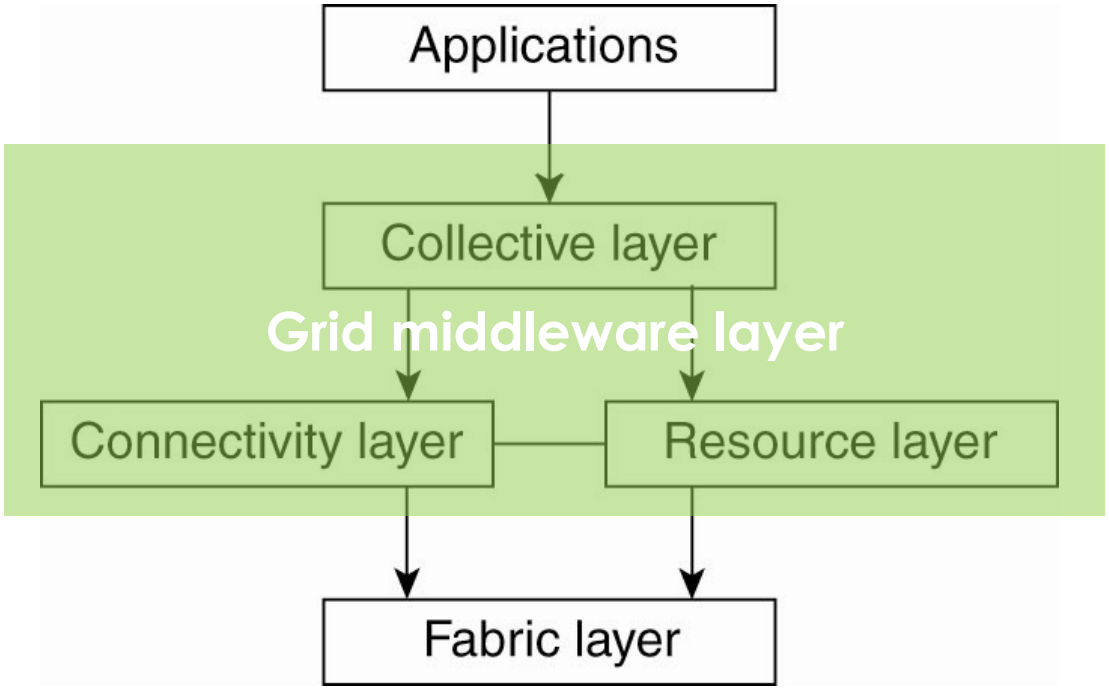
Highly heterogeneous with respect to hardware, software, networks, security policies, etc.

Grids support **virtual organizations**: a collaboration of users who pool resources (servers, storage, databases) and share them

Grid software is concerned with managing sharing across administrative domains.

A PROPOSED ARCHITECTURE FOR GRID SYSTEMS

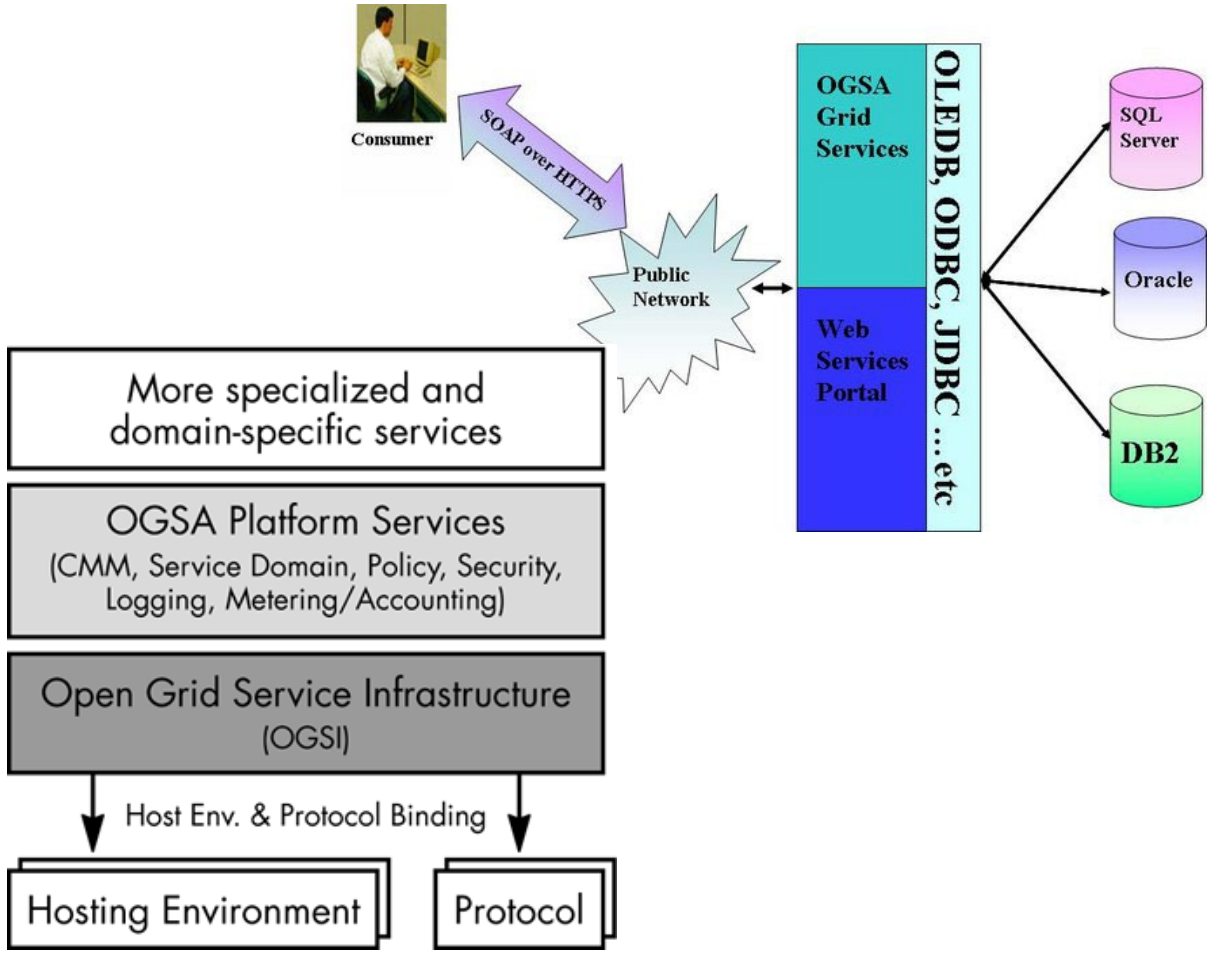
- **Fabric layer**: interfaces to local resources
- **Connectivity layer**: supports usage of *multiple resources* for a single application; e.g., access a remote resource or transfer data between sites
- **Resource layer** manages a *single resource*
- **Collective layer:** resource discovery, allocation, etc.
- **Applications**: use the grid resources
- The collective, connectivity and resource layers together form the middleware layer for a grid



. A layered architecture for grid computing systems

OGSA – ANOTHER GRID ARCHITECTURE

- Open Grid Services Architecture (OGSA) is a service-oriented architecture
  - Sites that offer resources to share do so by offering specific Web services.
- The architecture of the OGSA model is more complex than the previous layered model.



TYPES OF DISTRIBUTED SYSTEMS

- Distributed Computing Systems
  - Clusters
  - Grids
- Distributed Information Systems
  - Transaction Processing Systems
  - Enterprise Application Integration
- Distributed Embedded Systems
  - Home systems
  - Health care systems
  - Sensor networks

DISTRIBUTED INFORMATION SYSTEMS

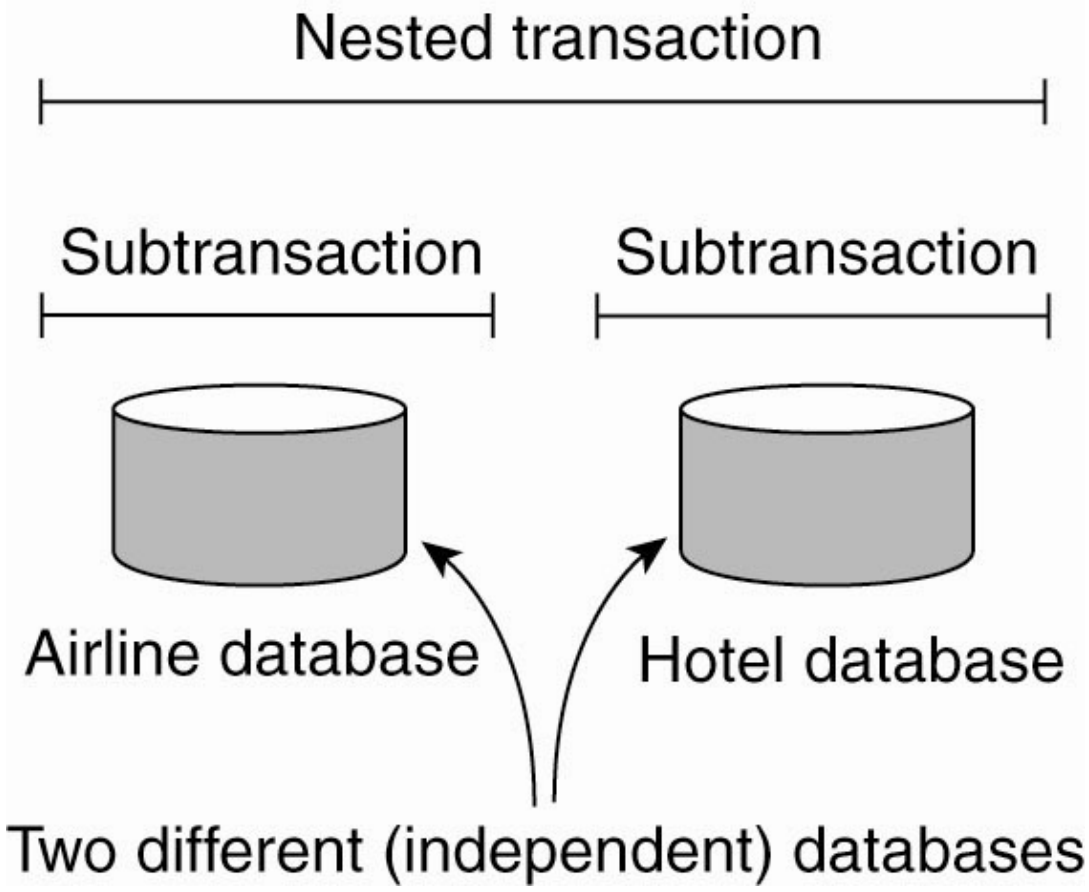
- Business-oriented
- Systems to make a number of separate network applications interoperable and build “enterprise-wide information systems”.
- Two types discussed here:
  - Transaction processing systems
  - Enterprise application integration

TRANSACTION PROCESSING SYSTEMS

- Provide a highly structured client-server approach for database applications
- Transactions are the communication model
- Obey the ACID properties:
  - Atomic: all or nothing
  - Consistent: invariants are preserved
  - Isolated (serializable)
  - Durable: committed operations can't be undone

Primitive	Description
BEGIN_TRANSACTION	Mark the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

TRANSACTION PROCESSING SYSTEMS



A nested transaction.

IMPLEMENTING TRANSACTIONS

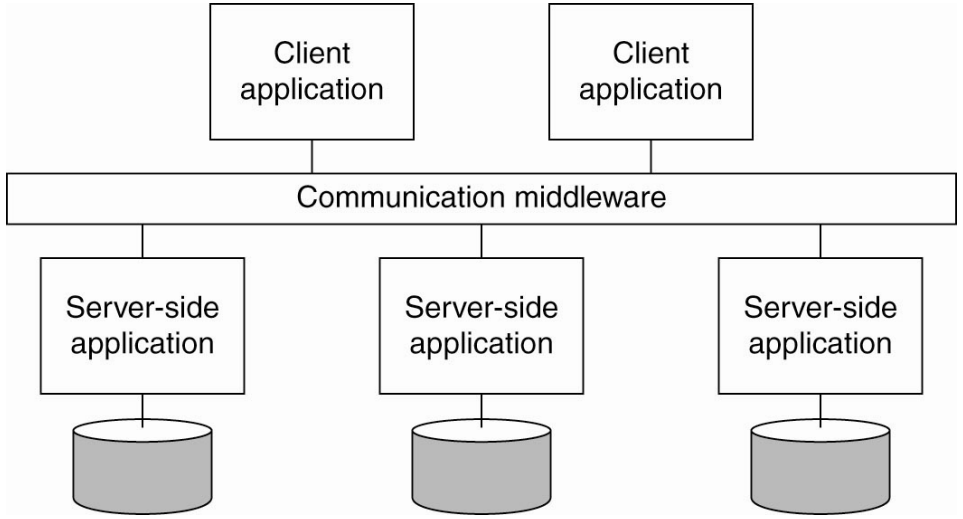
- Conceptually, private copy of all data
- Actually, usually based on logs
- Multiple sub-transactions – commit, abort
  - Durability is a characteristic of top-level transactions only
- Nested transactions are suitable for distributed systems
  - Transaction processing monitor may interface between client and multiple data bases.

ENTERPRISE APPLICATION INTEGRATION

- Supports a less-structured approach (as compared to transaction-based systems)
- Application components are allowed to communicate directly
- Communication mechanisms to support this include CORBA, Remote Procedure Call (RPC), Remote Method Invocation (RMI), and Message-Oriented middleware (MOM).

Examples?

Tell some software architectures that can be applied on this model



Middleware as a communication facilitator in enterprise application integration.

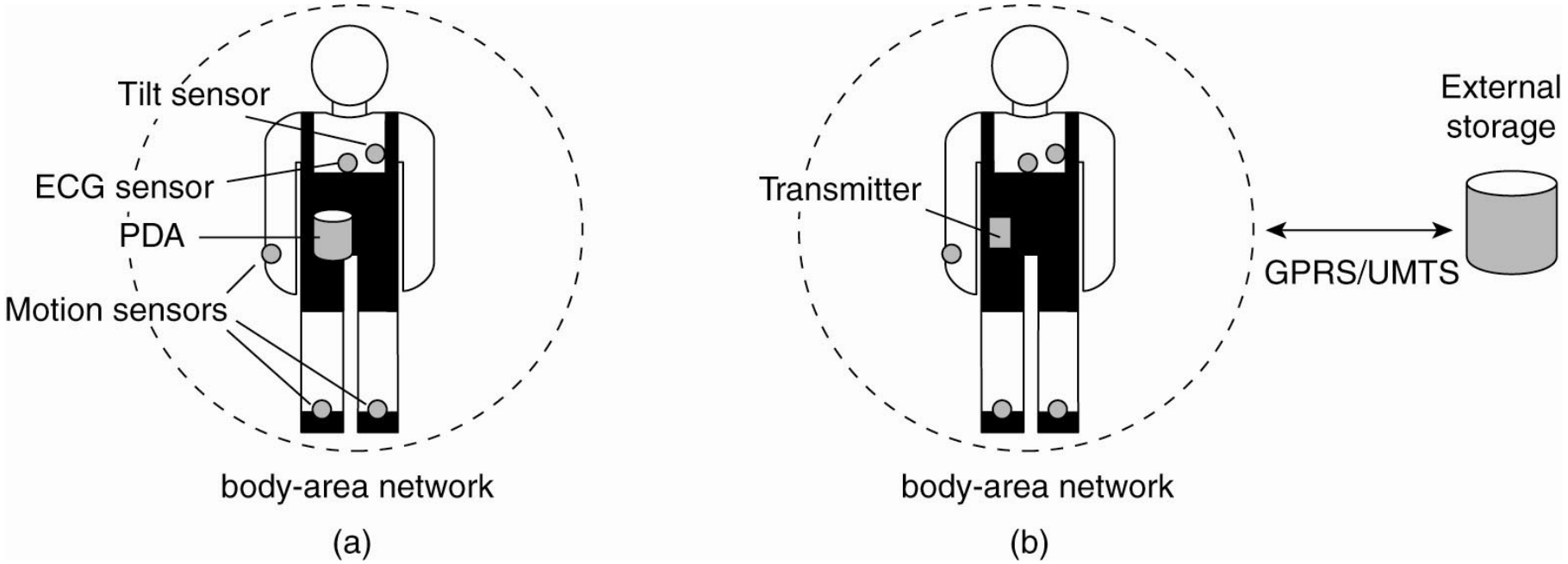
TYPES OF DISTRIBUTED SYSTEMS

- Distributed Computing Systems
  - Clusters
  - Grids
- Distributed Information Systems
  - Transaction Processing Systems
  - Enterprise Application Integration
- Distributed Embedded Systems
  - Home systems
  - Health care systems
  - Sensor networks

DISTRIBUTED PERVASIVE SYSTEMS

- The first two types of systems are characterized by their stability: nodes and network connections are more or less fixed
- This type of system is likely to incorporate small, battery-powered, mobile devices
  - Home systems
  - Electronic health care systems – patient monitoring
  - Sensor networks – data collection, surveillance

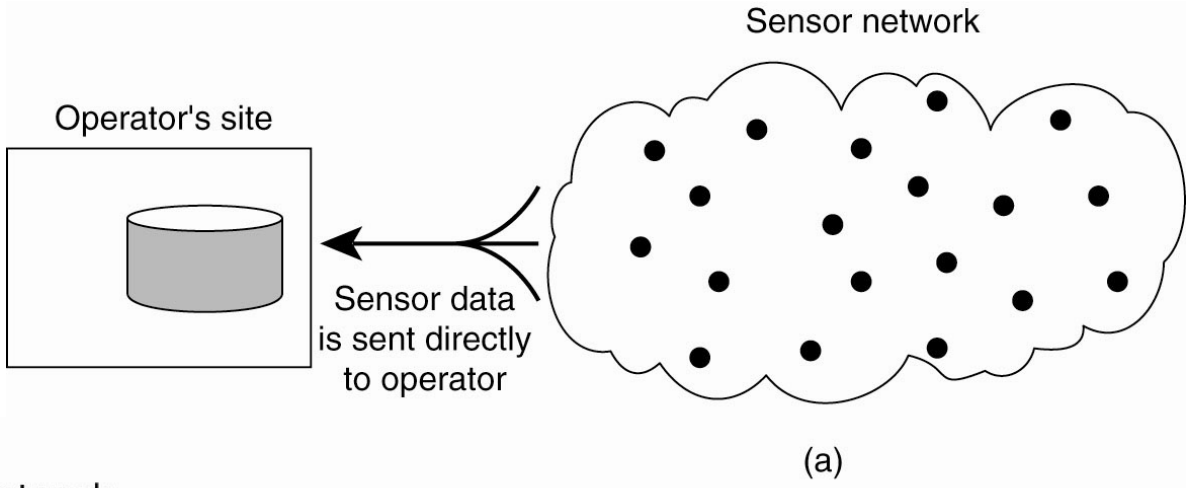
ELECTRONIC HEALTH CARE SYSTEMS

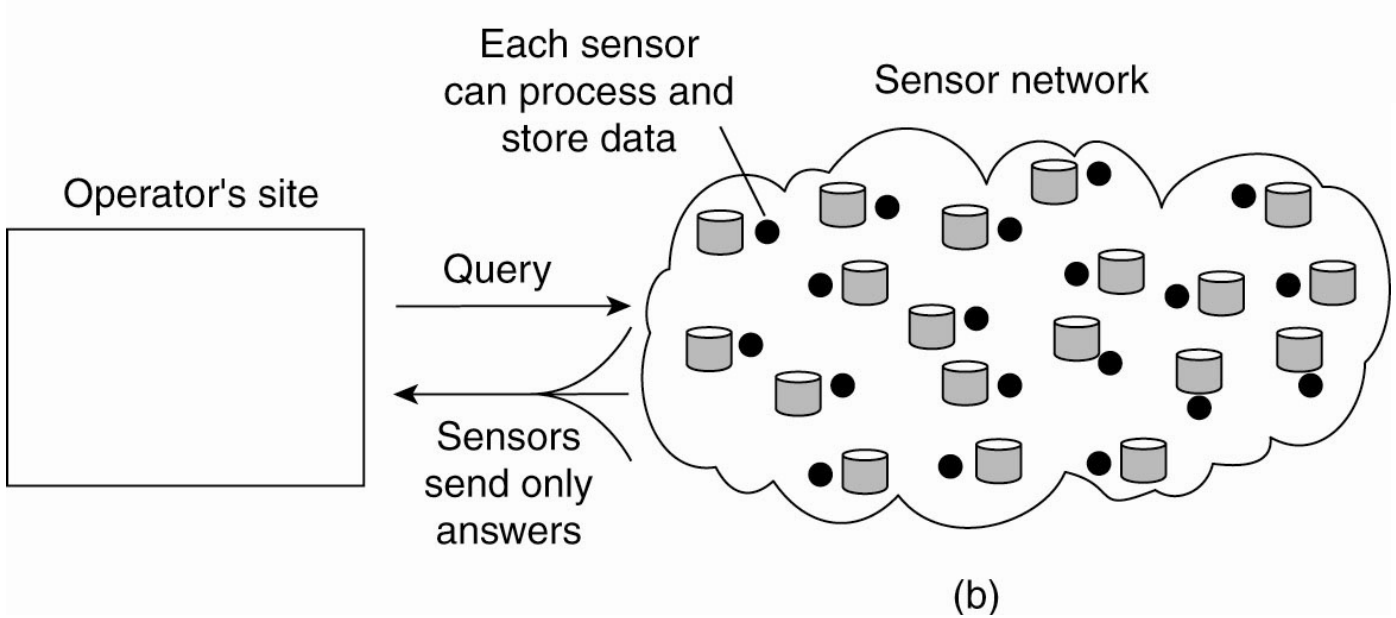


Monitoring a person in a pervasive electronic health care system, using (a) a local hub or (b) a continuous wireless connection.

SENSOR NETWORKS

Organizing a sensor network database, while storing and processing data (a) only at the operator's site or (b) only at the sensors.





Prof. Tim Wood & Prof. Roozbeh Haghnazar

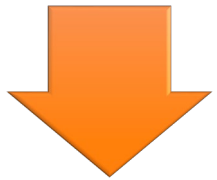
ARCHITECTURES

DEFINITION OF *ARCHITECTURE*

- The art or science of building
  - *specifically*: the art or practice of designing and building structures and especially habitable ones
- Formation or construction resulting from or as if from a conscious act or a unifying or coherent form or structure
- A method or style of building
- The manner in which the components of a computer or computer system are organized and integrated

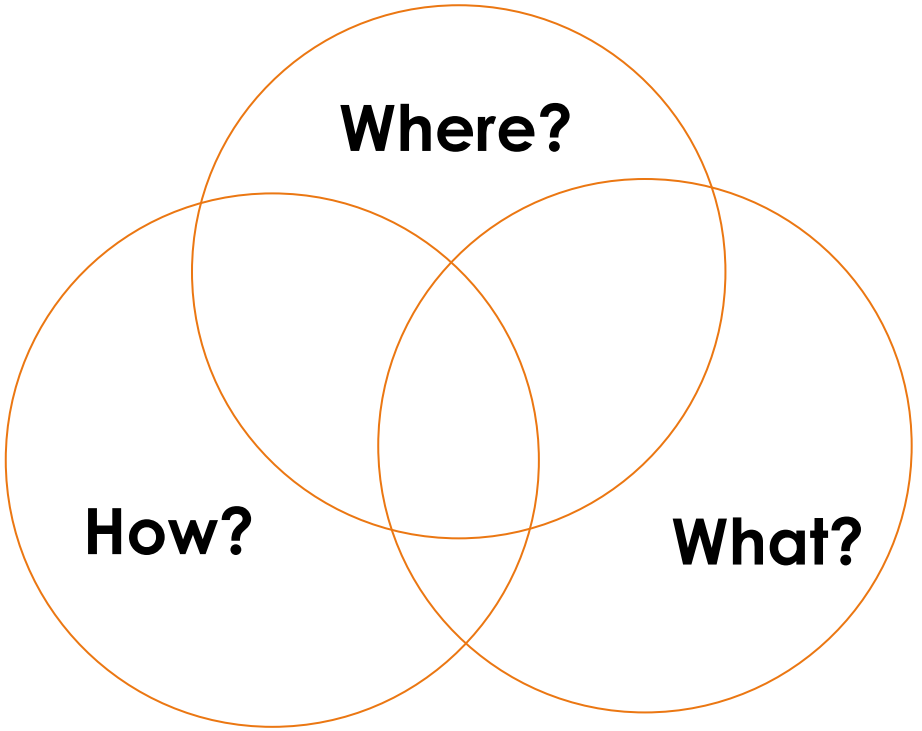
SOFTWARE/SYSTEM ARCHITECTURE

Software Architectures – describe the organization and interaction of software components; focuses on logical organization of software (component interaction, etc.)

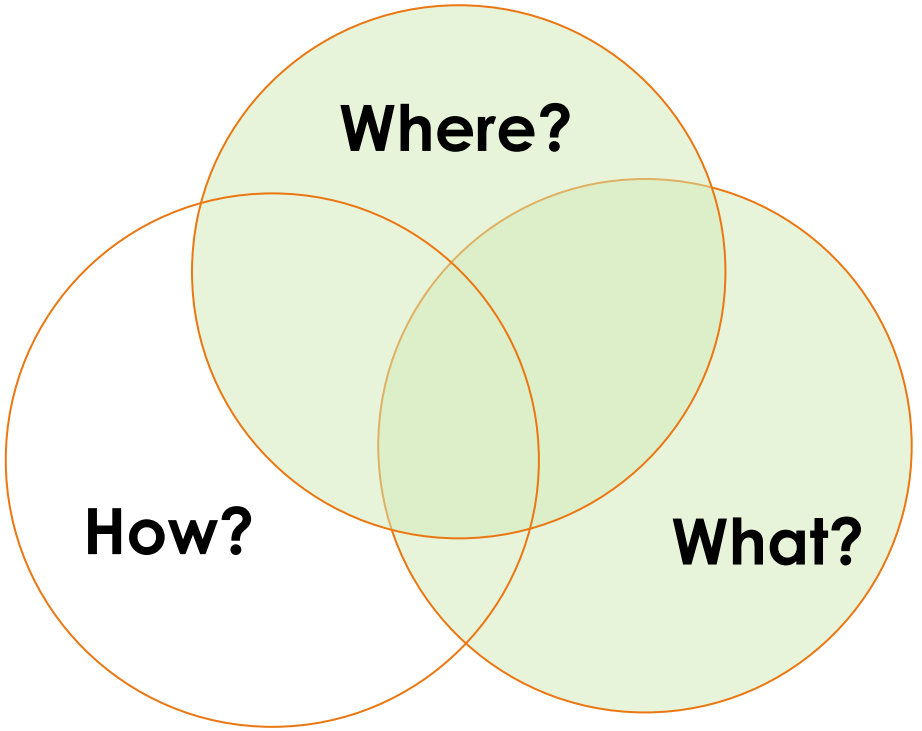


System Architectures - describe the communication and placement of software components on physical machines

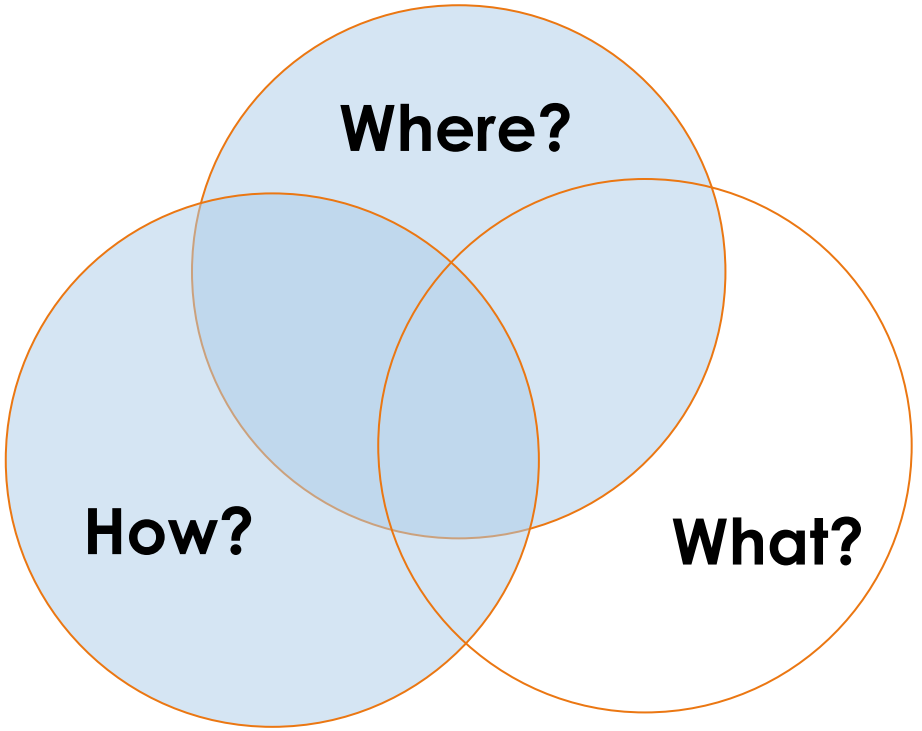
ARCHITECTURE VS DESIGN



ARCHITECTURE VS DESIGN

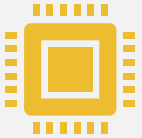


ARCHITECTURE VS DESIGN



COMPONENT

A component is an encapsulated part of a software system



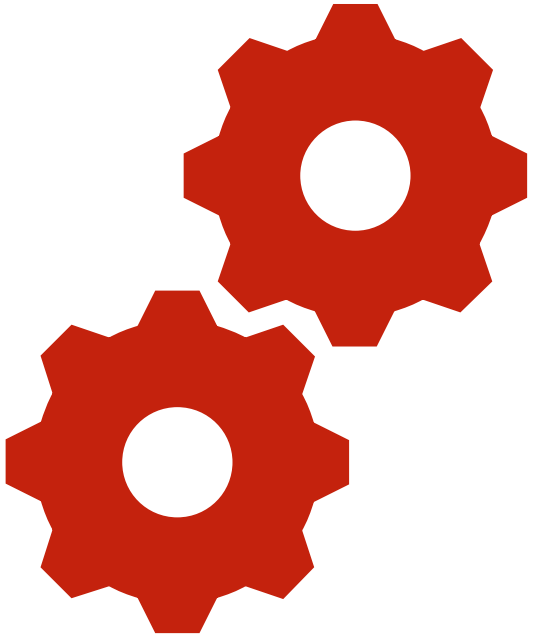
A component has an interface

Components serve as the building blocks for the structure of a system

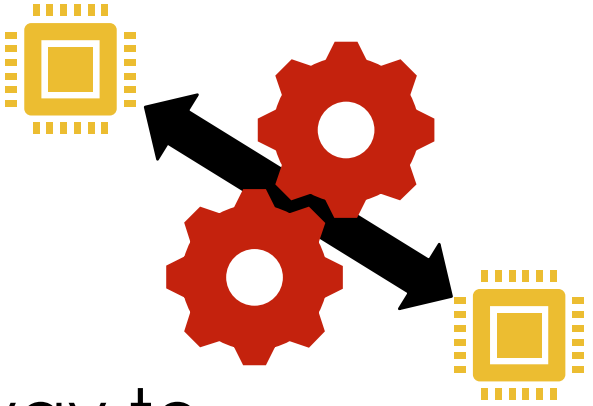
At a programming-language level, components may be represented as modules, classes, objects or as a set of related functions

SUBSYSTEM

- A subsystem is a set of collaborating components performing a given task
- A subsystem is considered a separate entity within a software architecture
  - It performs its designated task by interacting with other subsystems and components…



ARCHITECTURAL STYLES



- An **architectural style** describes a particular way to configure a collection of components and connectors.
  - **Component** - a module with well-defined interfaces; reusable, replaceable
  - **Connector** – communication link between modules

- An architectural style is a coordinated set of architectural **constraints** that restricts the relationships among those elements

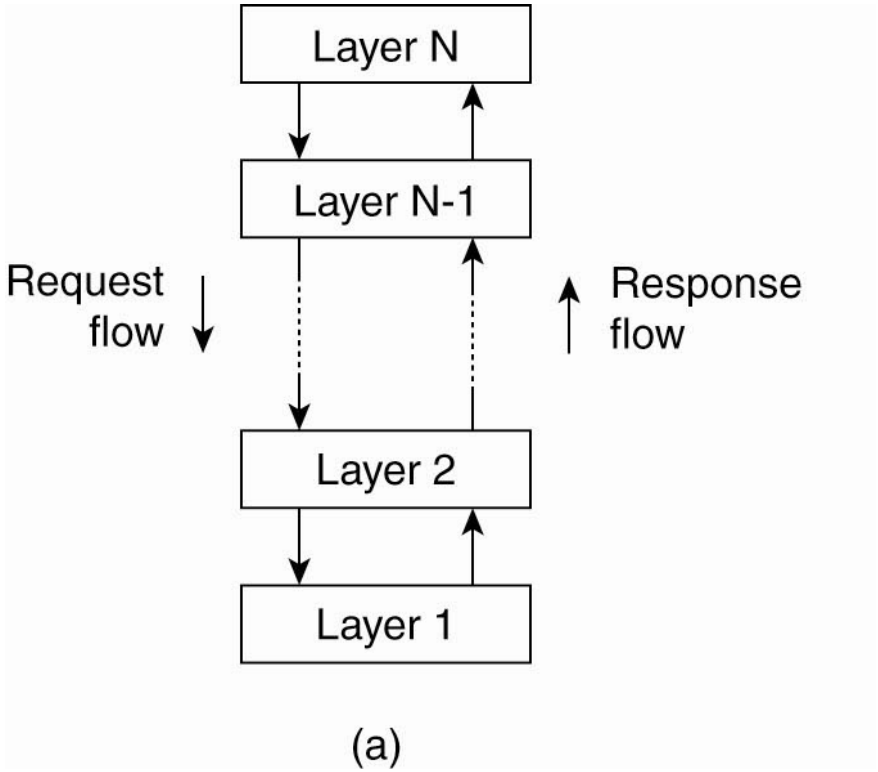
ARCHITECTURAL STYLES

1. Layered architectures
2. Object-based architectures
3. Data-centered architectures
4. Event-based architectures

1. LAYERED ARCHITECTURES

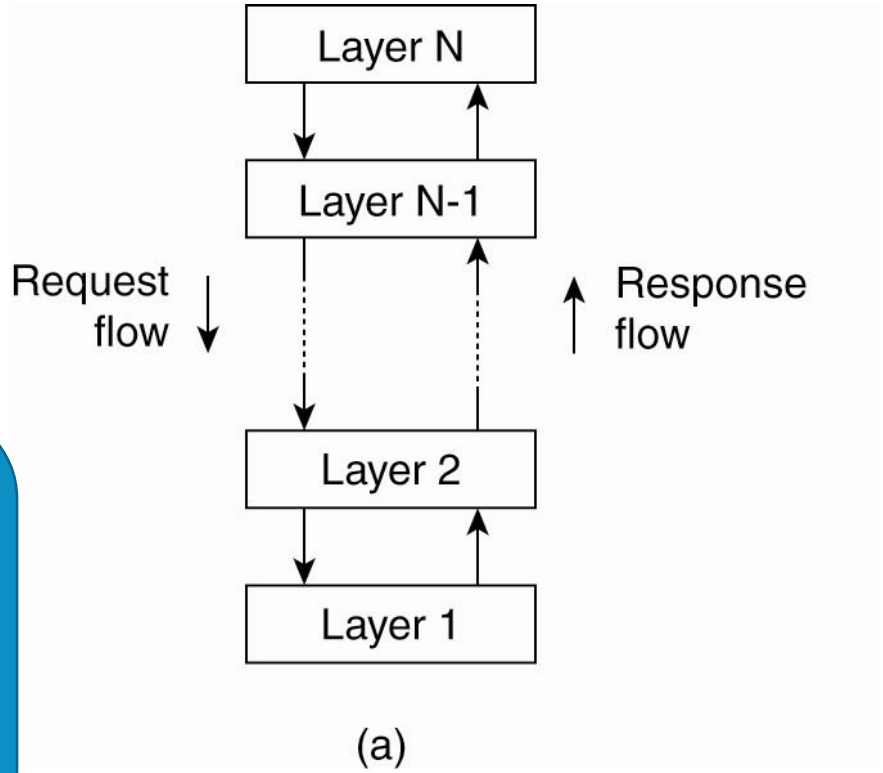
- Components of layer N_i is only allowed to call components at the underlying layer N_{i-1}

Why? Example?



1. LAYERED ARCHITECTURES

- Components of layer N_i is only allowed to call components at the underlying layer N_{i-1}

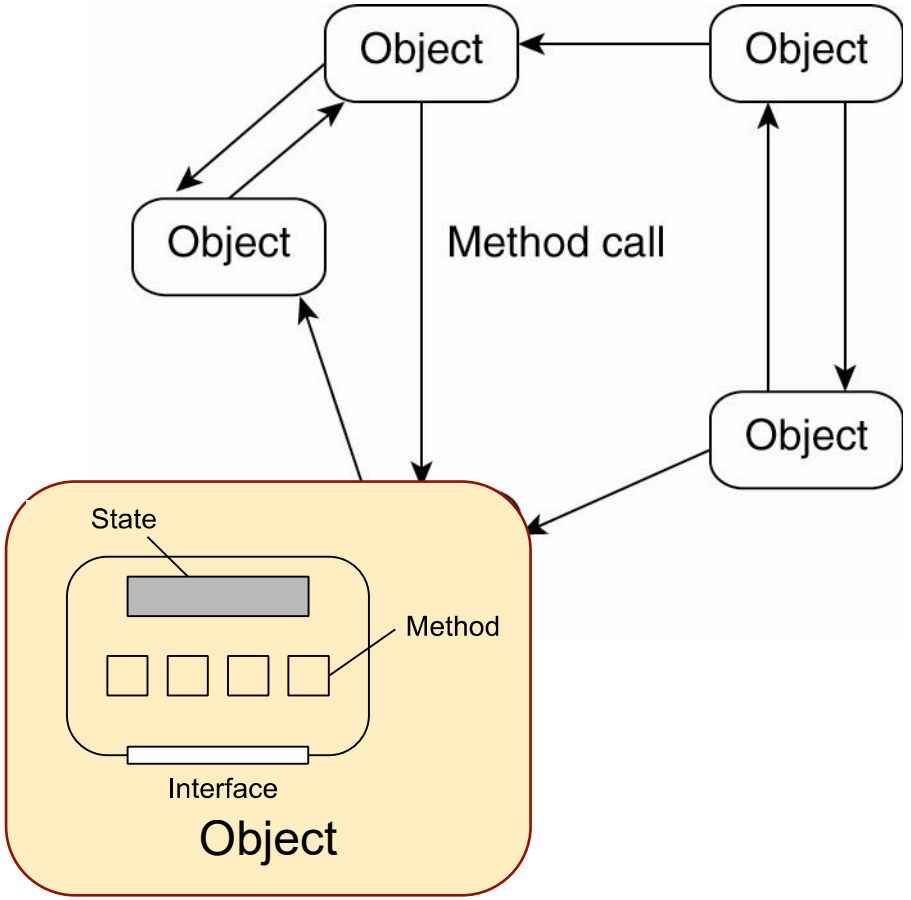


Why: hides information, interchangeable layers
Example: Network stack, LAMP stack

2. OBJECT-BASED ARCHITECTURES

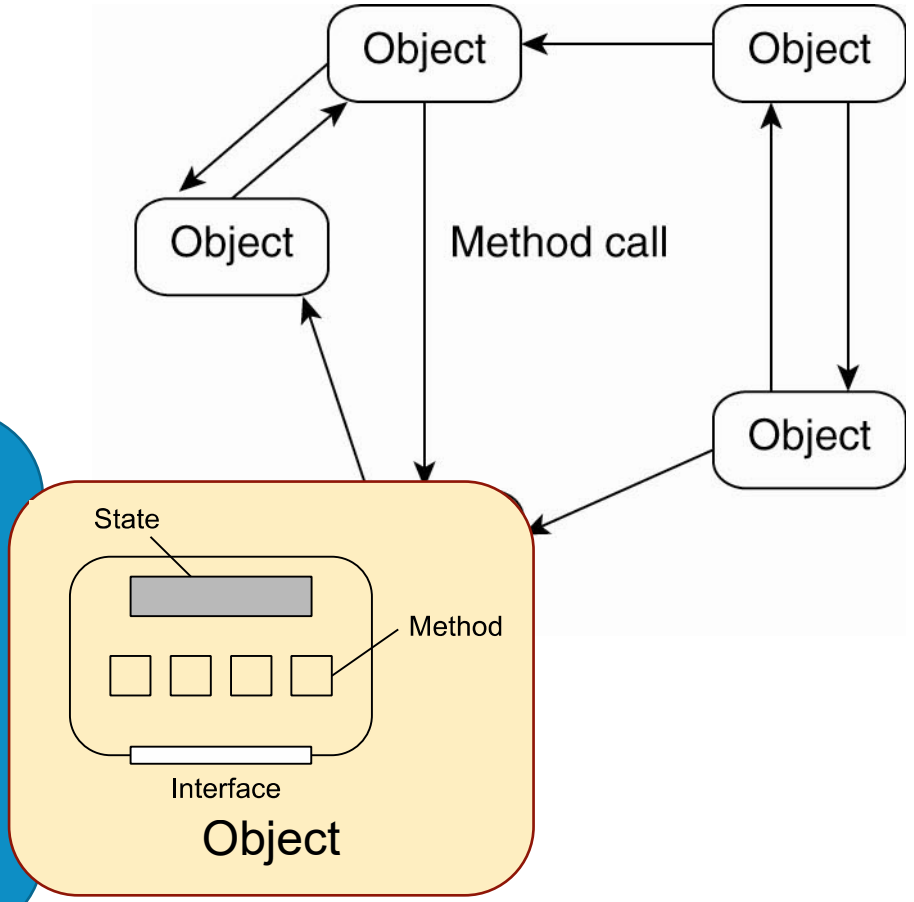
- Each object is a component that encapsulates data and methods
- They are connected through a well defined remote API that hides internals

Why? Example?



2. OBJECT-BASED ARCHITECTURES

- Each object is a component that encapsulates data and methods
- They are connected through a well defined remote API that hides internals

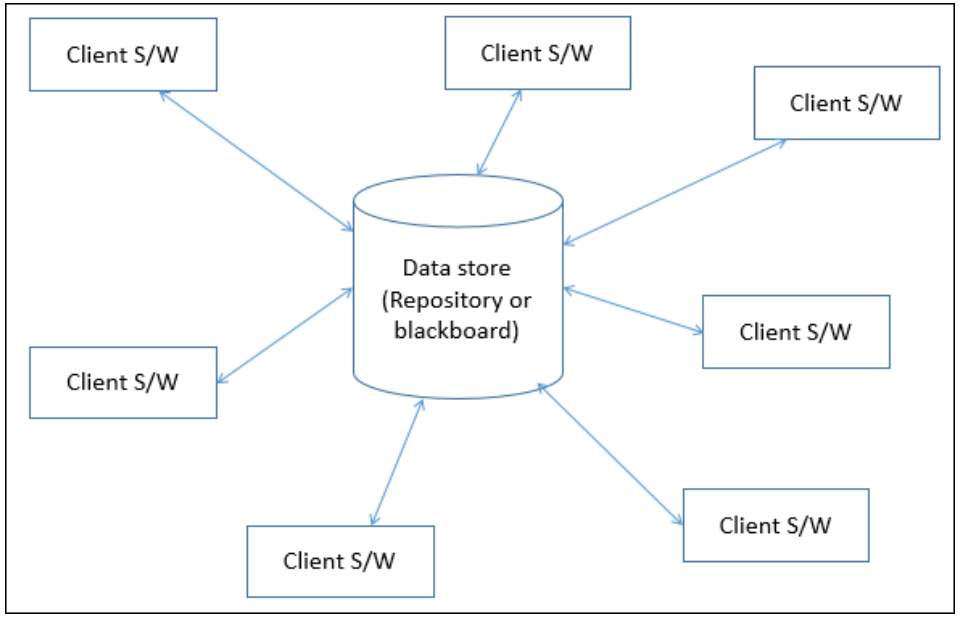


Why: components can be individually scaled/developed/managed
Example: MapReduce, microservice web architectures

3. DATA-CENTERED ARCHITECTURES

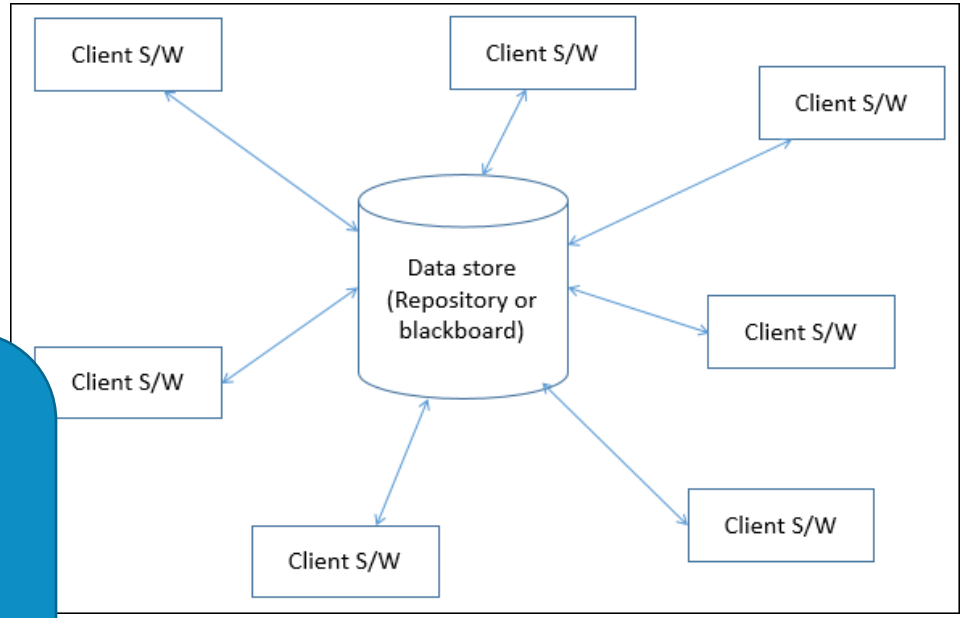
- Main purpose: data access and update
- Processes interact by reading and modifying data in a **centralized** shared repository

Why? Example?



3. DATA-CENTERED ARCHITECTURES

- Main purpose: data access and update
- Processes interact by reading and modifying data in a **centralized** shared repository

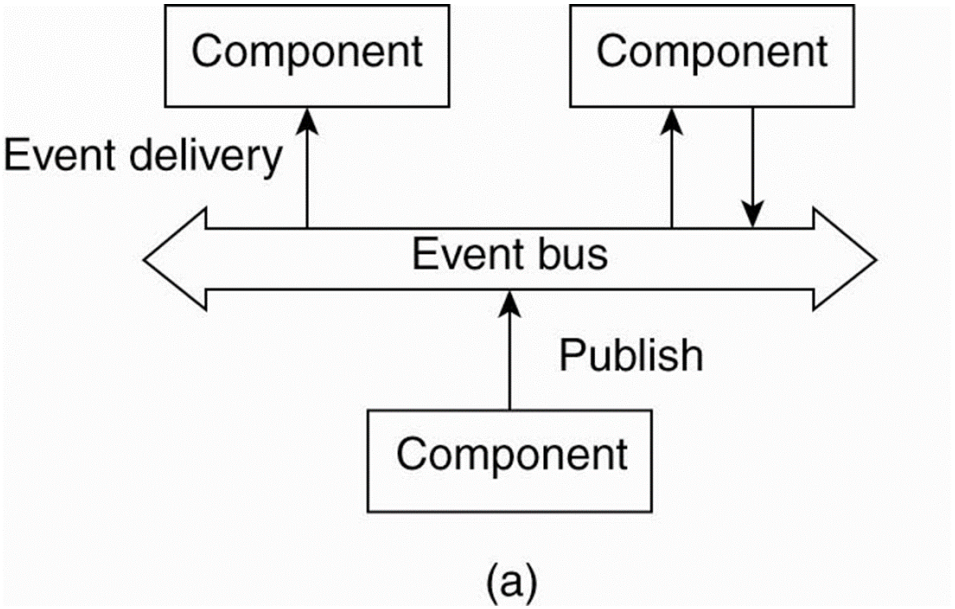


Why: simplifies data management
Example: Dropbox, Message board systems, Email

4. EVENT-BASED ARCHITECTURES

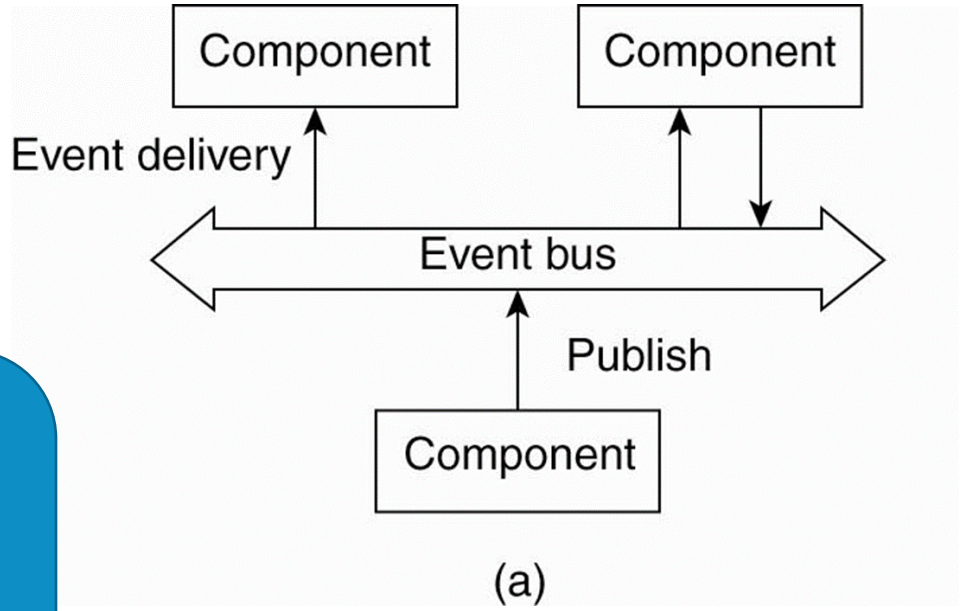
- Communication via event propagation
  - Publish-subscribe
  - Broadcast
  - Point-to-point

Why? Example?



4. EVENT-BASED ARCHITECTURES

- Communication via event propagation
  - Publish-subscribe
  - Broadcast
  - Point-to-point



Why: decouples sender/receiver, asynchronous
Example: Slack, Security monitoring

ARCHITECTURAL STYLES

1. Layered architectures
2. Object-based architectures
3. Data-centered architectures
4. Event-based architectures

Each style constrains how we will build the system. Following a style makes development and extensibility easier.

But sometimes we need a **hybrid** style!

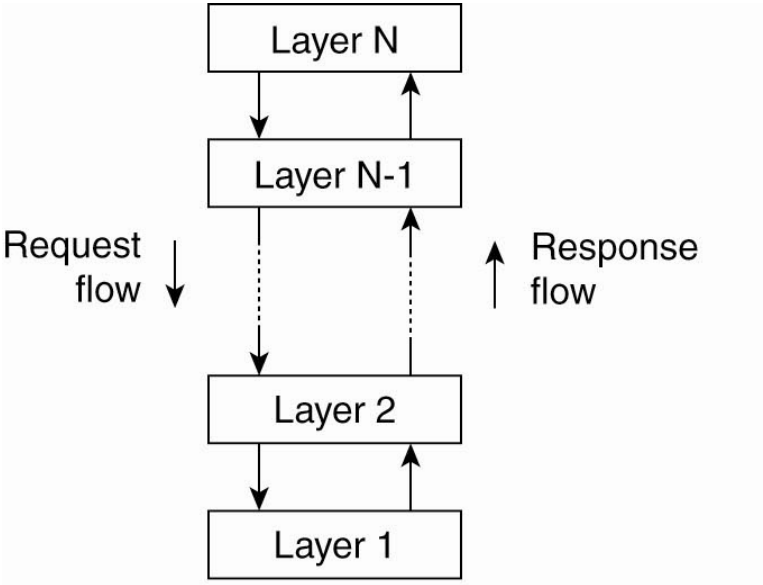
SYSTEM CHARACTERISTICS

- **Centralized**: A single component/subsystem is "in charge"
  - **Vertical** (or hierarchical) organization of communication and control paths
  - Logical separation of functions into client (requester) and server (responder)
- **Decentralized**: multiple components/subsystems interact as peers
  - **Horizontal** rather than hierarchical communication and control
  - Communication paths may be less structured; symmetric functionality
- **Hybrid:** combine elements of both

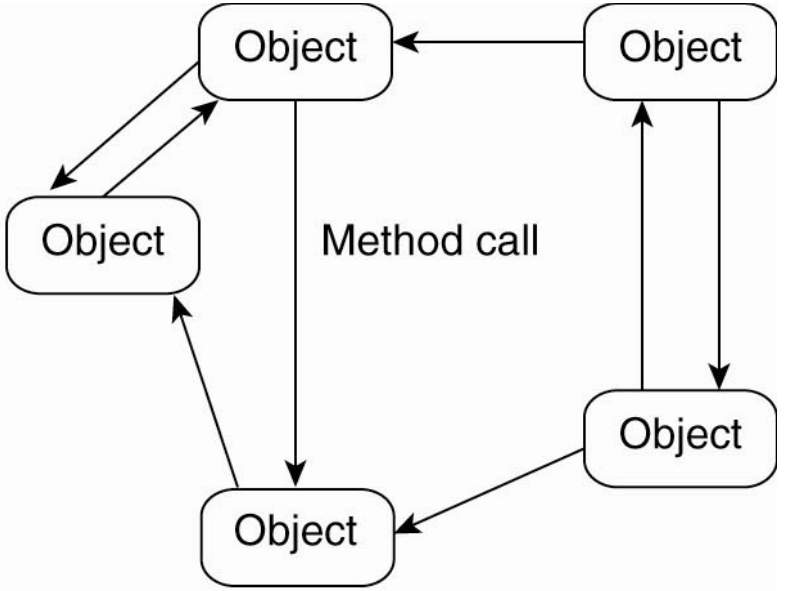
Classification of a system as **centralized** or **decentralized** primarily refers to **communication** and **control organization**

VERTICAL VS HORIZONTAL

- Vertical: Layers with different functionality. Restricted communication

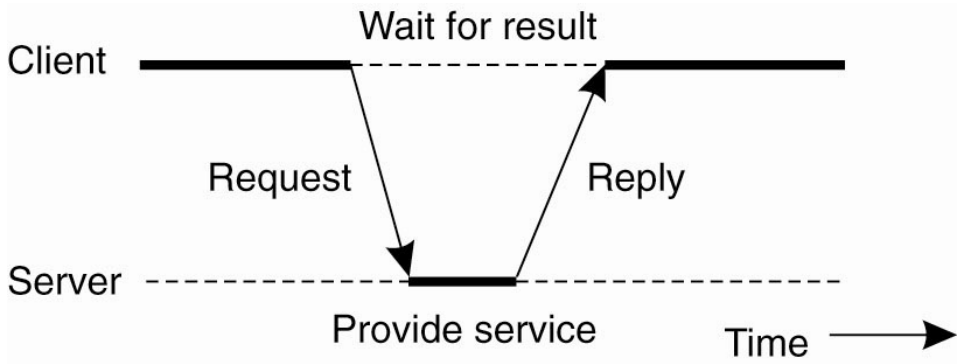


- Horizontal: Components with similar functionality or more diverse communication



TRADITIONAL CLIENT-SERVER

- Processes are divided into two groups (clients and servers).
- Synchronous communication: request-reply protocol
  - Could be message oriented or RPC



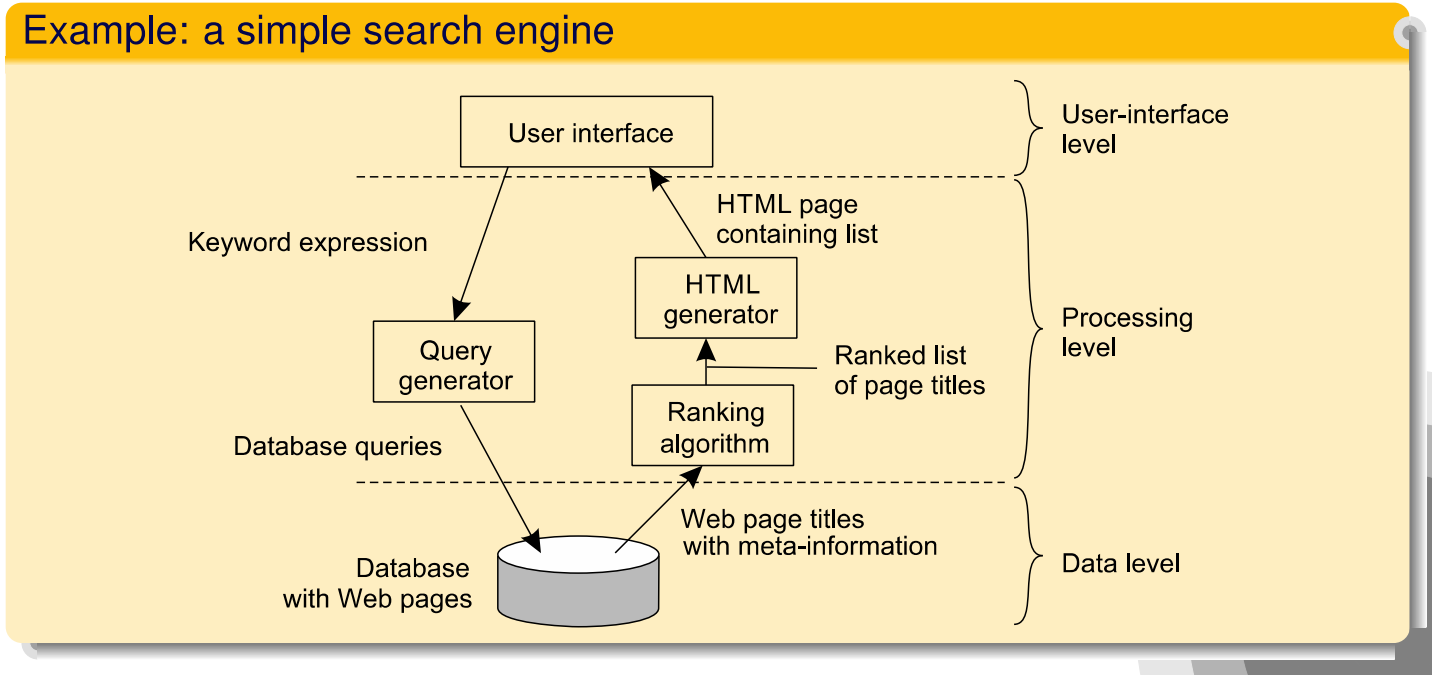
- Note: even in this simple example, lots could go wrong!

CLIENT ARCHITECTURE

- Server provides processing and data management; client provides simple graphical display (**thin-client**)
  - Pro: Easier to manage, more reliable, client machines don't need to be so large and powerful
  - Con: Potential performance loss at client
- At the other extreme, all application processing and some data resides at the client (**fat-client** approach)
  - Pro: reduces workload at server; more scalable
  - Con: harder to manage by system admin, less secure

LAYERED SERVER EXAMPLE

- **User-interface level**: GUI's (usually) for interacting with end users
- **Processing level**: data processing applications – the core functionality
- **Data level**: interacts with data base or file system



TIERS, LAYERS, NODES, COMPONENTS

- ***Layer*** and ***tier*** are roughly equivalent terms, but *layer* typically implies software and *tier* is more likely to refer to component deployment on HW.
  - Several software layers might comprise a subsystem deployed as a single "tier" in a multi-tier web application
- **Components** are generally software, whereas a **node** could refer to a component deployed on a particular server

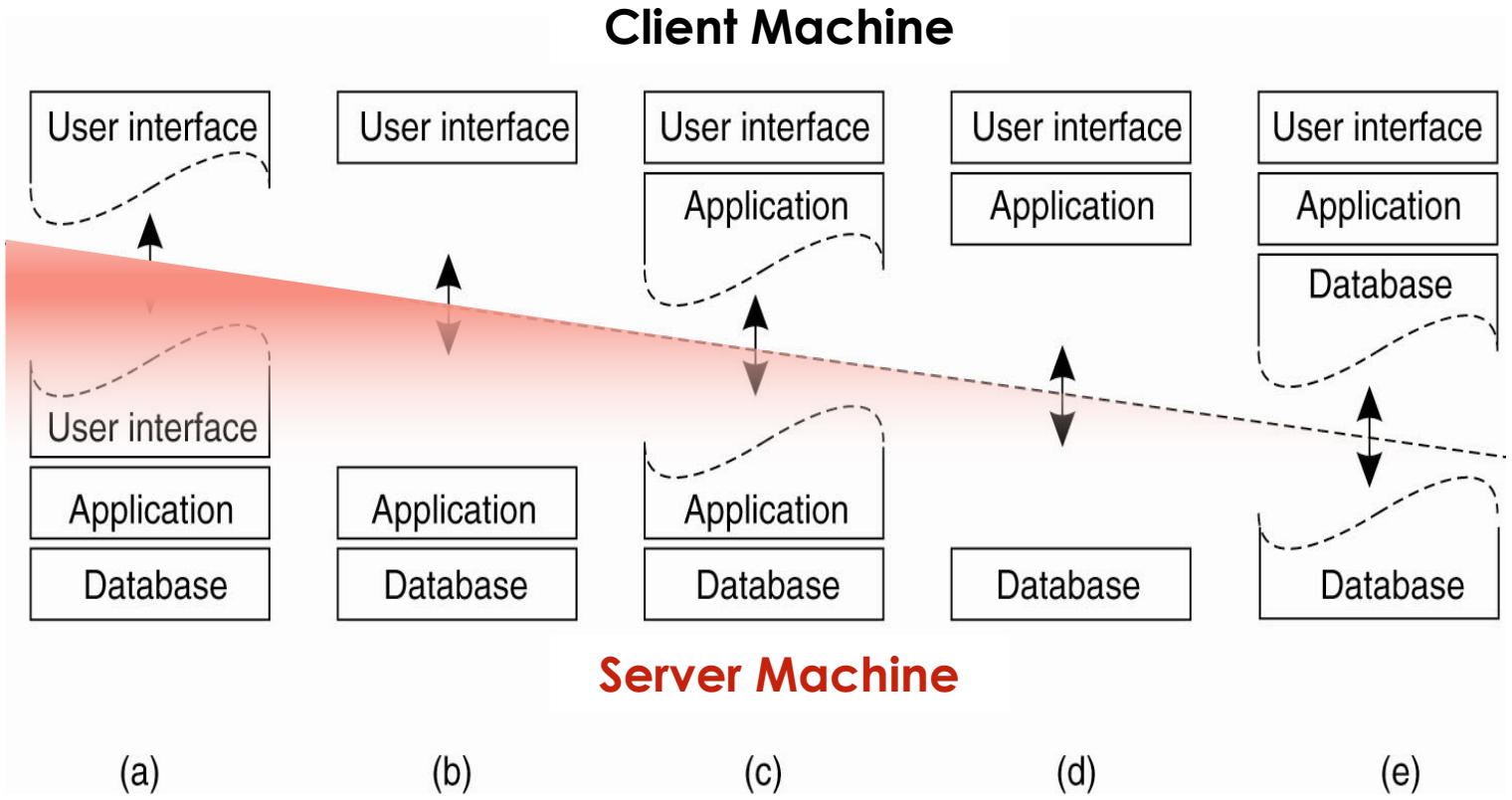
Layers / Components = Software

Tiers / Nodes = Software deployed on hardware

(usually*)

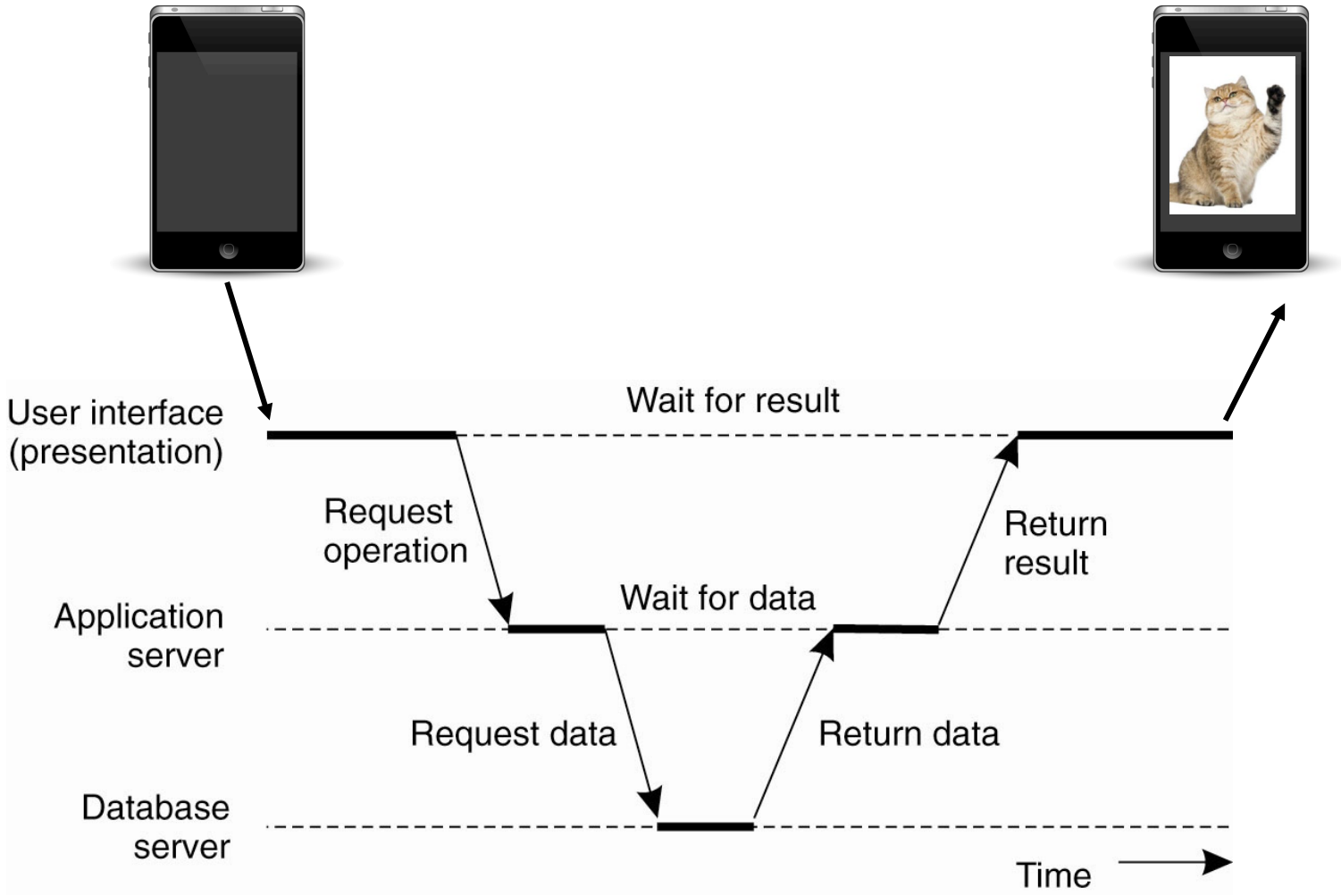
CLIENT-SERVER SPLIT

Can you come up with an example service/application which uses each of these architectures?



THREE-TIERED WEB ARCHITECTURE

- Tiers can be spread across multiple servers
- Simplifies deployment, performance management, reliability
- Servers also can play the role of client



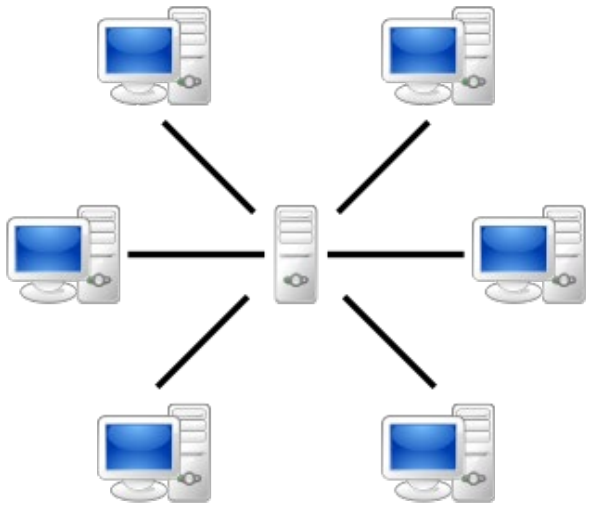
"LAMP Stack" (Linux, Apache, MySQL, PHP) was the 3-tier standard

Prof. Tim Wood & Prof. Roozbeh Haghnazar

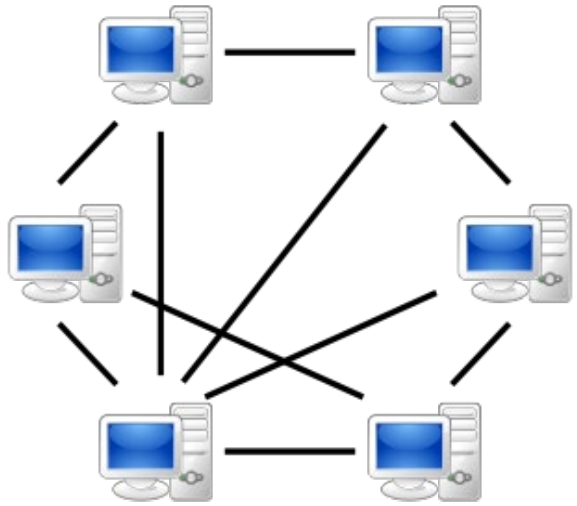
DECENTRALIZED ARCHITECTURES

PEER TO PEER SYSTEMS

- A distributed system that does not rely on centralized coordination
- Peers are *equipotent* and work together to provide a service



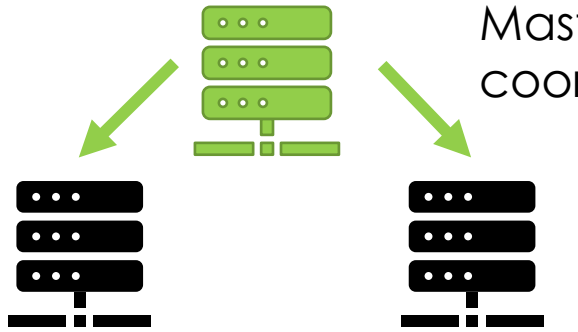
Centralized



P2P

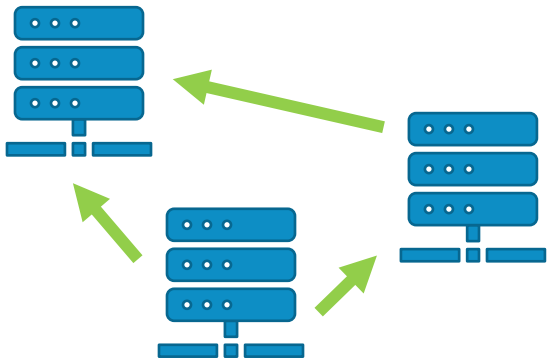
DECENTRALIZATION BENEFITS

- Centralized systems may have **a single point of failure**
  - Affects reliability and may be a performance bottleneck



Master/Leader node coordinates followers

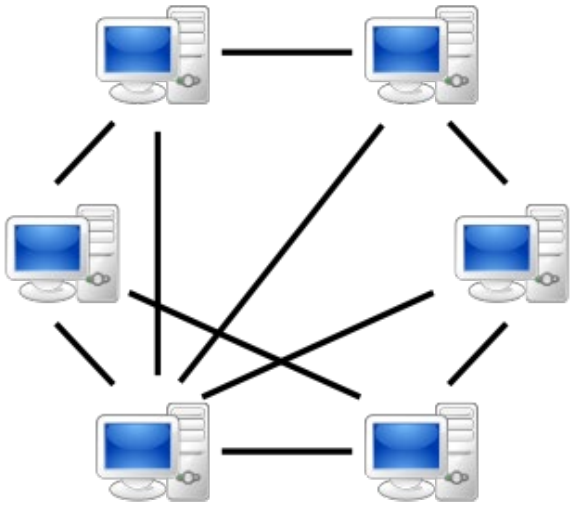
- Decentralization can make a system **more robust and performant**
  - But only if it is well designed!



Peer-to-Peer system can self-organize

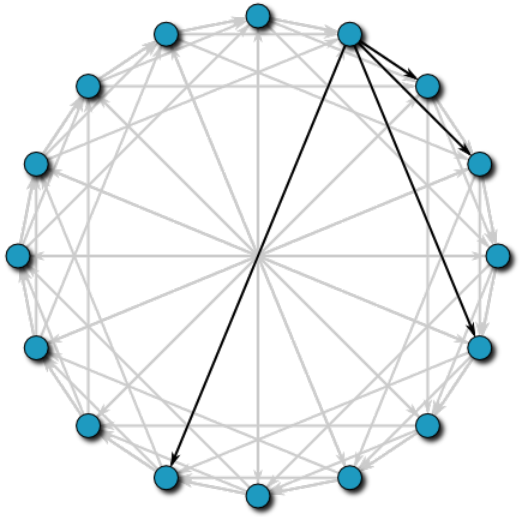
P2P CHALLENGES

- Routing and Discovery
  - How to reach other nodes?
  - How to find out what other nodes exist?
  - How to bootstrap when you first join?
- Consistency
  - How to keep information consistent across the network?
- Reliability / Failure Handling
  - What happens when nodes crash and rejoin?
- Performance
  - How to get predictable performance with limited control?

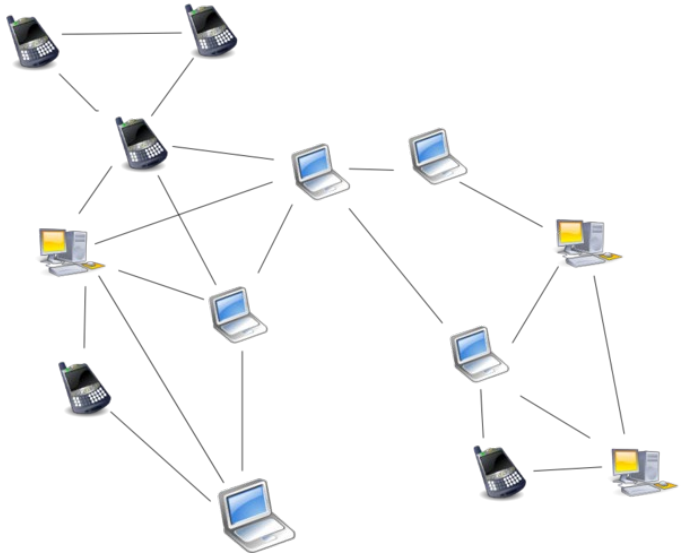


P2P ARCHITECTURES

Structured



Unstructured

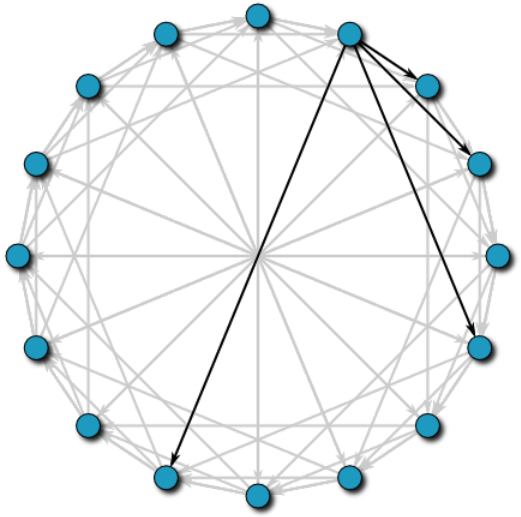


- The **peers** can be connected in a organized (**structured**) manner or in an ad-hoc (**unstructured**) manner
  - **Why/When might you choose one over the other?**

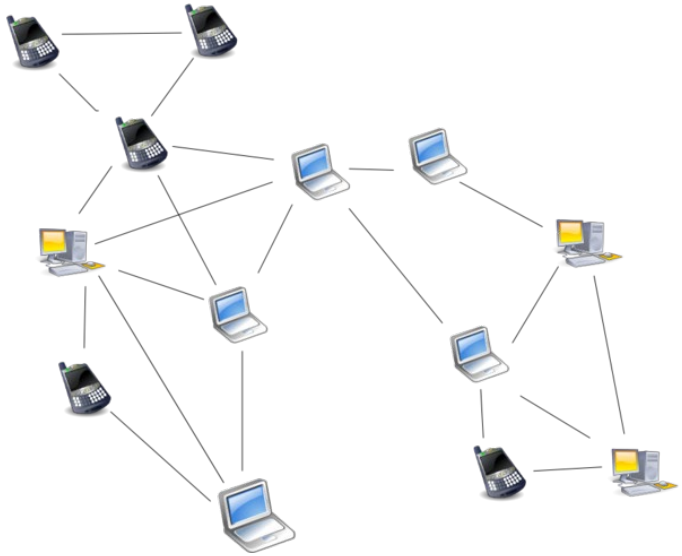
Figures from wikipedia

BOOTSTRAPPING

Structured



Unstructured

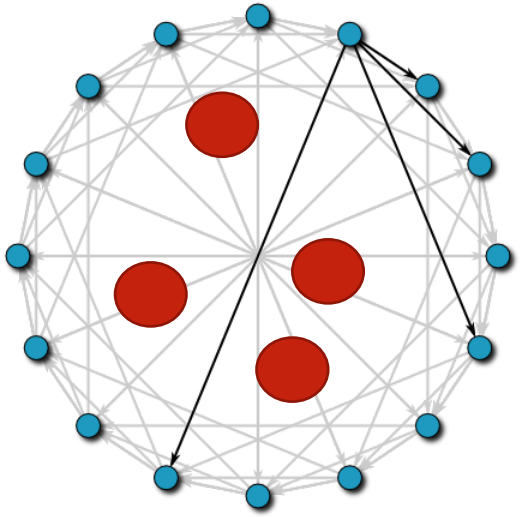


- How can a node join a P2P network if there is no centralized server to connect to?

Figures from wikipedia

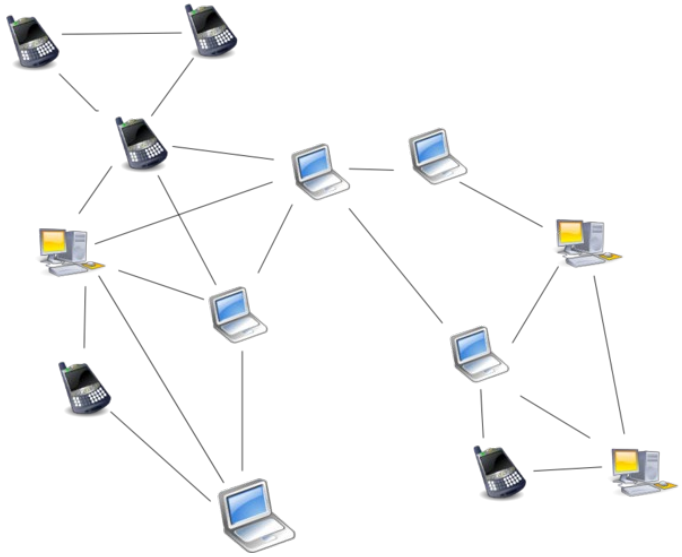
BOOTSTRAPPING

Structured



- Common Assumptions:
  - New nodes have address of at least one other active node
  - Special peers store extra information

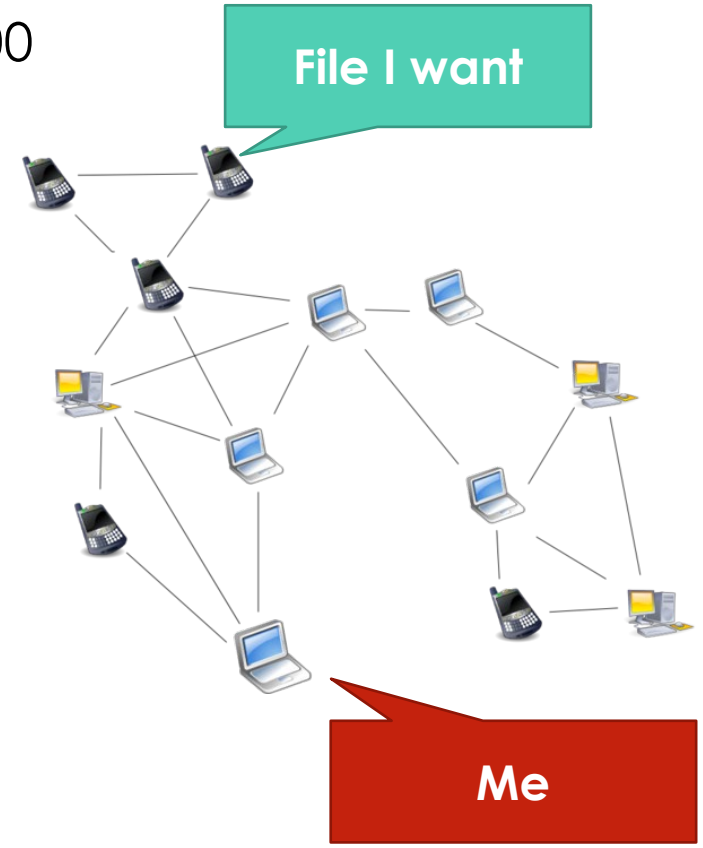
Unstructured



- New nodes can broadcast on their radio to find close neighbors

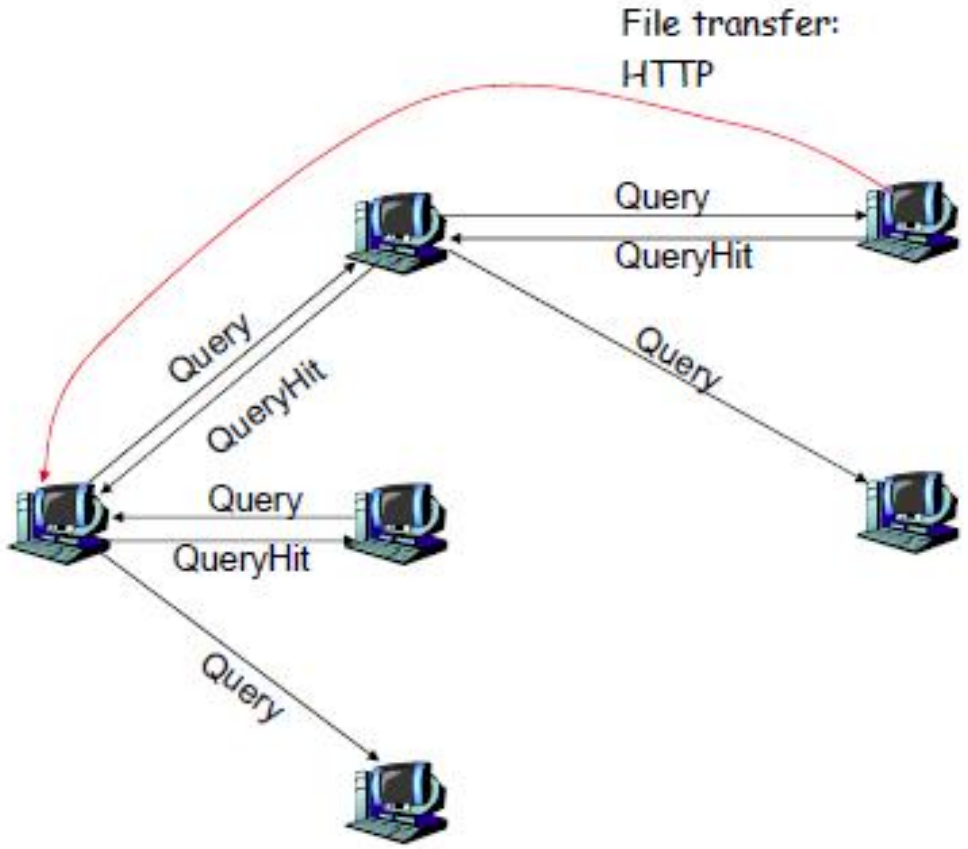
GNUTELLA P2P FILE SHARING

- Peer-to-Peer file sharing service
  - Released by a company owned by AOL on March 14, 2000
  - AOL shut down the company the next day…
- **Unstructured** P2P system
  - Bootstrap using pre-defined addresses of starter nodes
  - Randomly pick a set of N neighbors (N=5)
  - Search for files by querying neighbors
  - Neighbors propagate searches up to H hops total (H=7)
  - Responses travel back the same path
- Once file is found, transfer over direct connection



GNUTELLA

- At most how many neighbors will this search?
  - 5 neighbors per node
  - 7 hop max path
- This is a form of *flooding*
- What could make this more efficient?



Figures from wikipedia

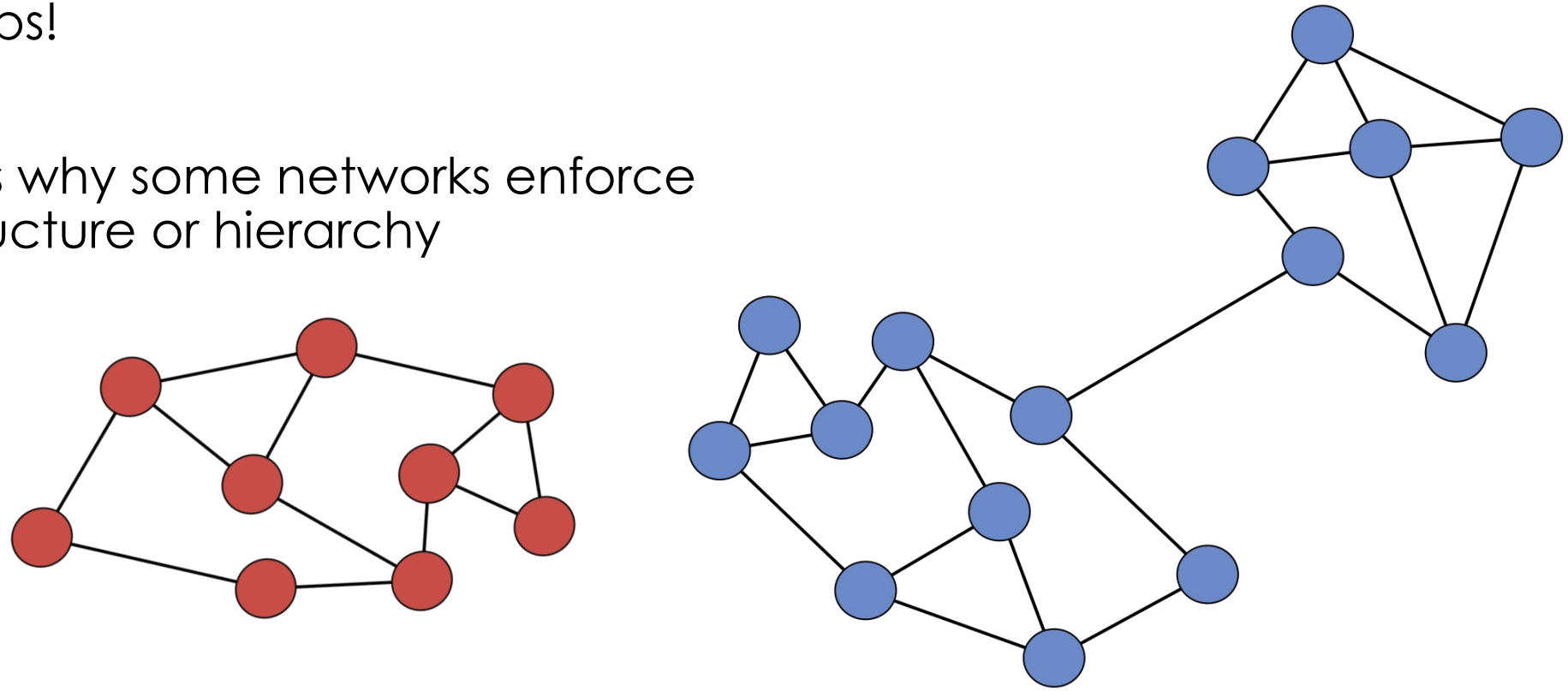
NOT ALL PEERS ARE EQUAL

- Gnutella v0.6 added Ultra Peers and Leaves
- Leaf Node:
  - Connects to 3 Ultra Peers
  - Maintains an index of all its content
  - Send queries to Ultra Peer
- Ultra Peer:
  - Connects to 32 Ultra Peers
  - Forwards queries at most 4 hops (not 7)
  - Merges the content indexes of all leaf nodes
  - Shares content index with all adjacent Ultra Peers
  - Only send to an Ultra peer on the 4th hop if query is in index
- How does this change things?

How to Pick Neighbors?

- Want to avoid disconnected components and weak connectivity between groups!

- This is why some networks enforce a structure or hierarchy

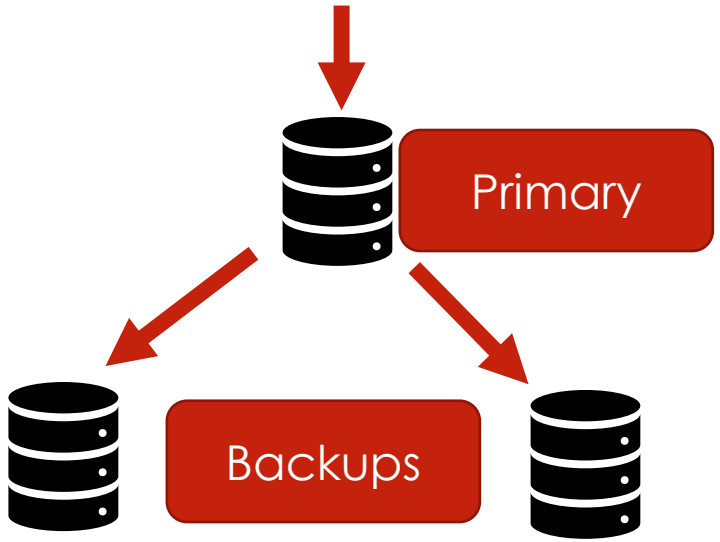


EXTRA SLIDES

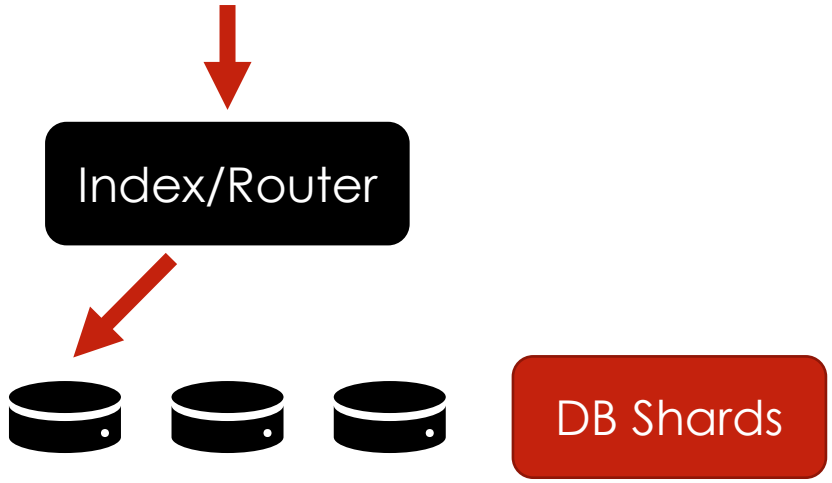
For later…

SEMI-DECENTRALIZED

- Replicated Database
  - All writes go to Primary
  - Reads can be distributed



- Sharded Database
  - Requests are routed to different DB "shards" that store part of data

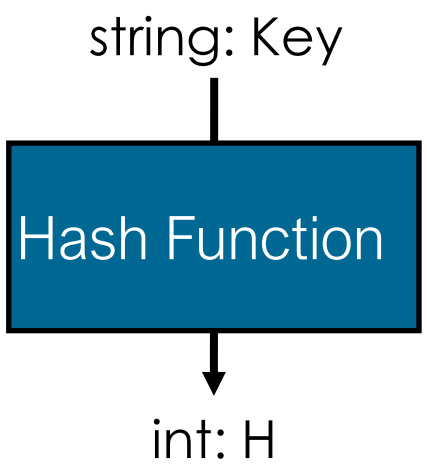


FULLY DECENTRALIZED P2P

- How to design a fully decentralized Key Value store?
  - Record <Key, Value> pairs like a hash table
- Distributed Hash Table (DHT) goals:
  - Evenly partition data across nodes
  - Efficiently find where data is stored
  - Gracefully handle nodes joining/leaving

SIMPLE HASH TABLE

- Find the value for a key in an array



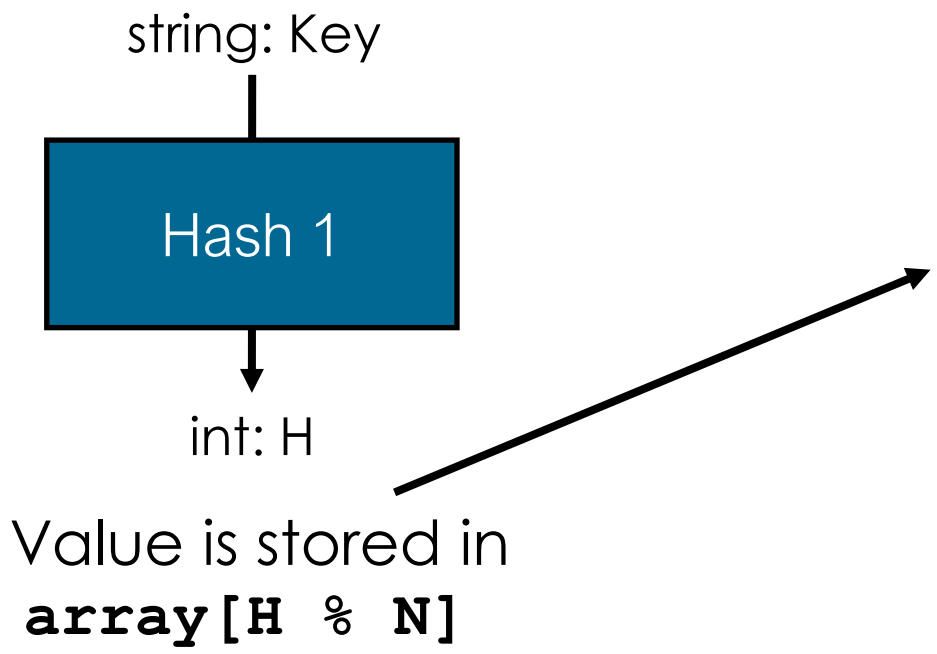
Value is stored in
`array[H % S]`

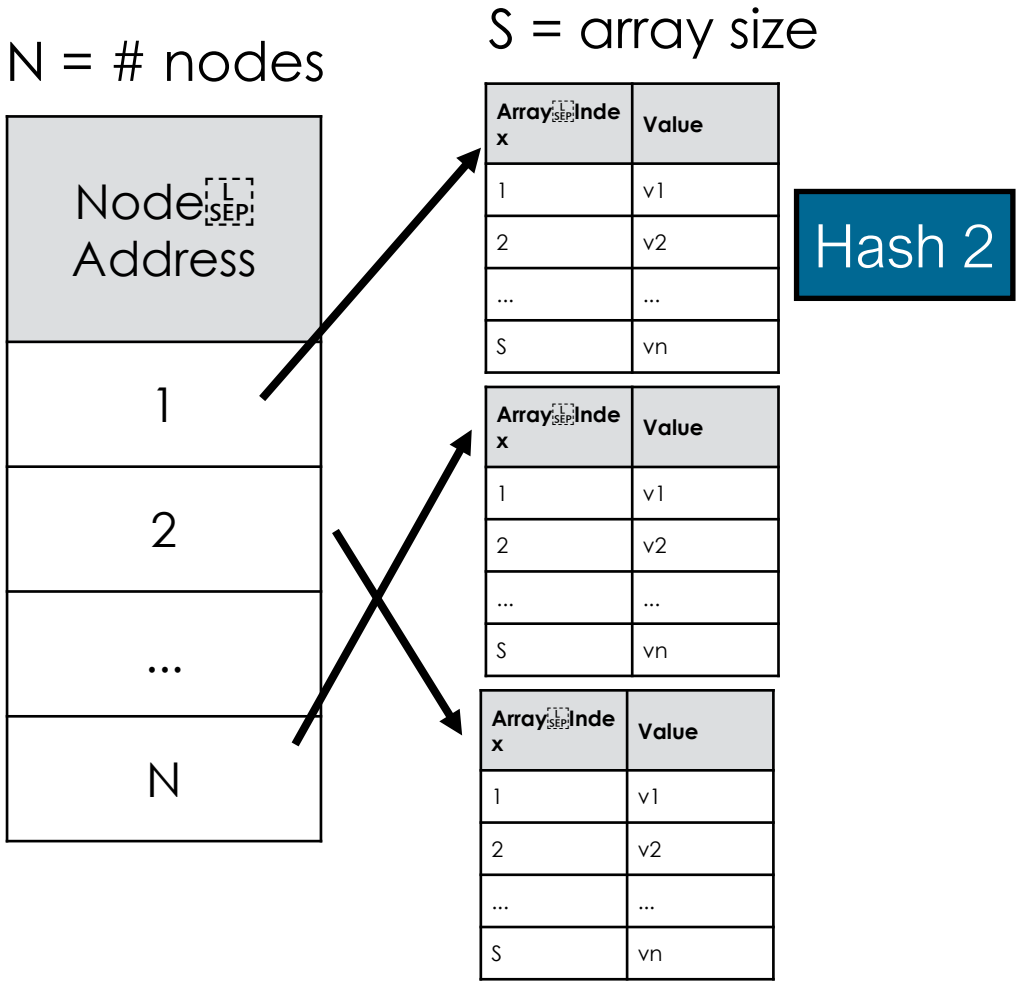
S = array size

Array Index	Value
1	v1
2	v2
…	…
S	vs

SIMPLE DHT V1

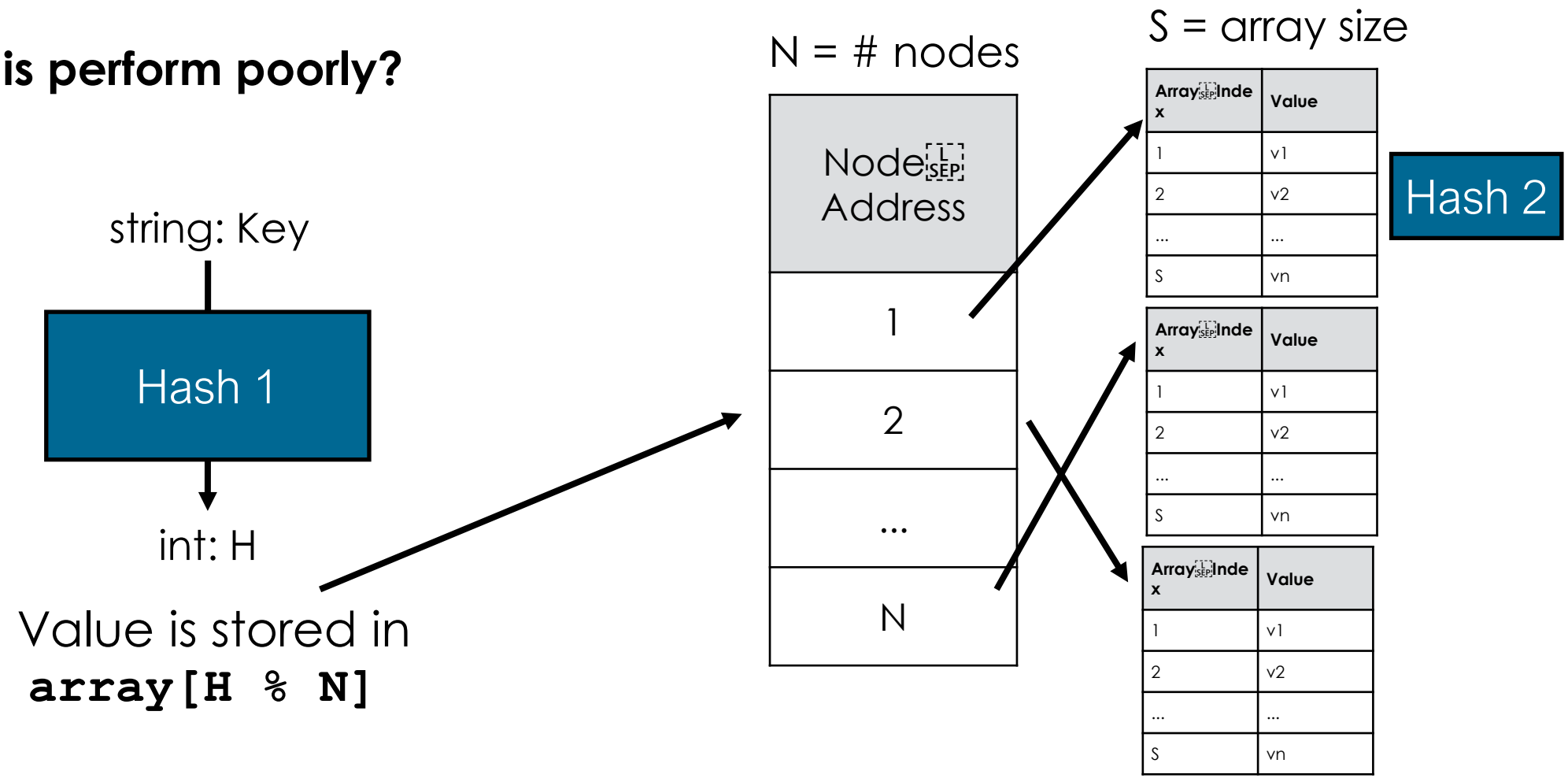
- What if one node can't fit all the data?
- Do two hash lookups!





SIMPLE DHT V1

- **When will this perform poorly?**

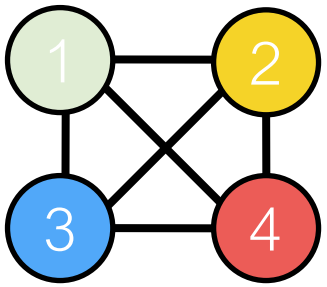


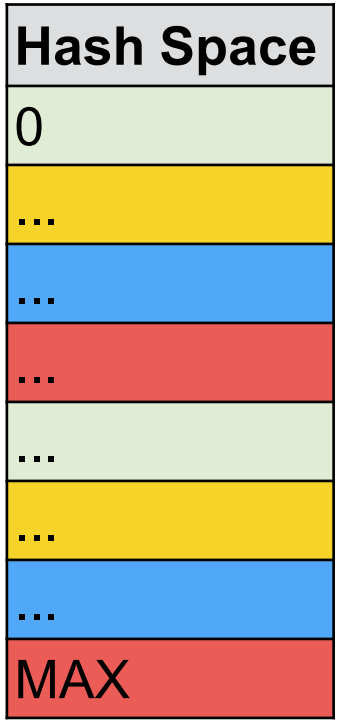
DHT CHURN

- Churn is when nodes are frequently joining or leaving
  - In a DHT it is OK to lose data when a node leaves, but it shouldn't cause all other nodes to reshuffle their data!

Simple DHT

Value is stored on
`node[H % 4]`





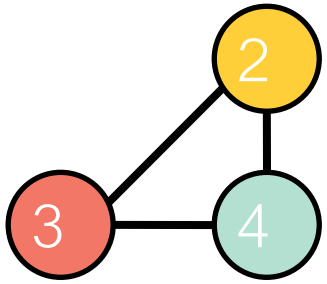
Divides hash space into 4 equal partitions for 4 servers

CHURN

- Churn is when nodes are frequently joining or leaving
  - In a DHT it is OK to lose data when a node leaves, but it shouldn't cause all other nodes to reshuffle their data!

Hash Space
0
…
…
…
…
…
…
MAX

Oops!
Green node
failed!



Hash Space
0
…
…
…
…
…
…
MAX

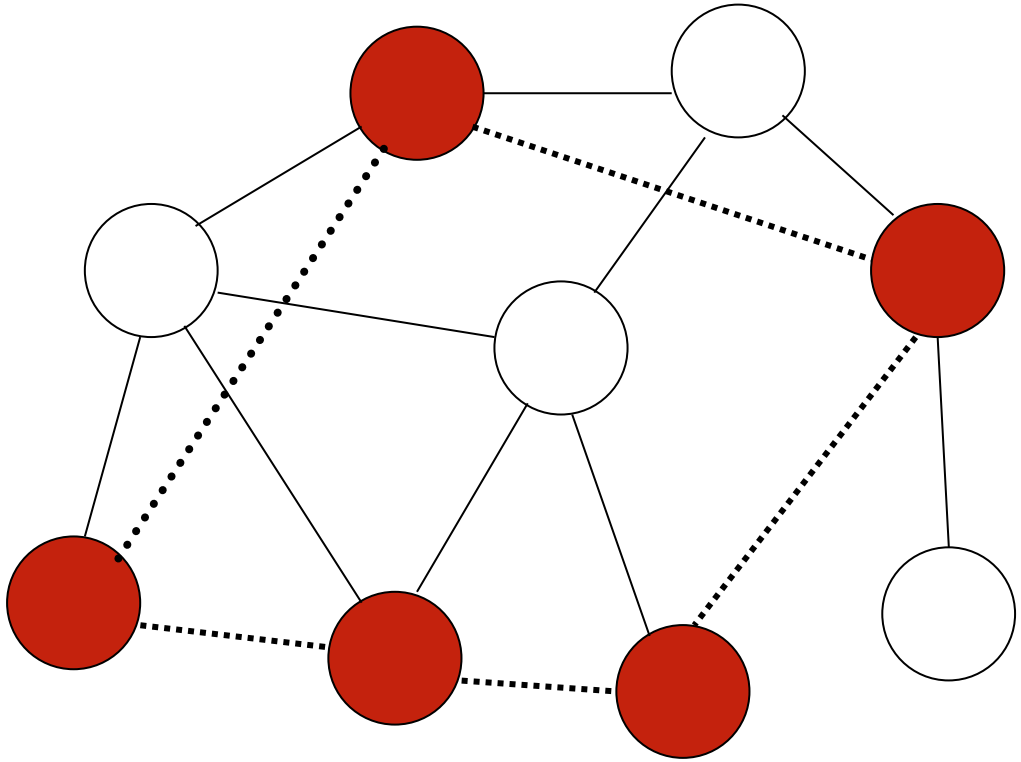
All nodes
needs to be
reorganized!

STRUCTURED PEER TO PEER

- Symmetric behavior, peer-to-peer architectures evolve around the question how to organize the processes in an **overlay network**, that is, a network in which the nodes are formed by the processes and the links represent the possible communication channels.
- The overlay network is constructed using a deterministic procedure.
- By far the most-used procedure is to organize the process through a **distributed hash table(DHT)**

OVERLAY NETWORK

- Are logical or *virtual* networks, built on top of a physical network
- A link between two nodes in the overlay may consist of several physical links.
- Messages in the overlay are sent to logical addresses, not physical (IP) addresses
- Various approaches used to resolve logical addresses to physical.



DISTRIBUTED HASH TABLE

- Allows you to insert, delete and lookup objects with keys
- Performance concerns:
  - Load balancing
  - Fault tolerance
  - Efficiency of lookup and inserts
  - Locality
- Napster, Gnutella, FastTrack, etc. are kind of DHT

CHARACTERISTICS OF DHT

- Scalable – to thousands, even millions of network nodes
  - Search time increases more slowly than size; usually O(log(N))
- Fault tolerant – able to re-organize itself when nodes fail
- Decentralized – no central coordinator
  (example of decentralized algorithms)

STRUCTURED P2P ARCHITECTURES

- In a DHT, data objects and nodes are each assigned a key which hashes to a random number from a very large identifier space (to ensure uniqueness)
- A mapping function assigns objects to nodes, based on the hash function value.
- A lookup, also based on hash function value, returns the network address of the node that stores the requested object.

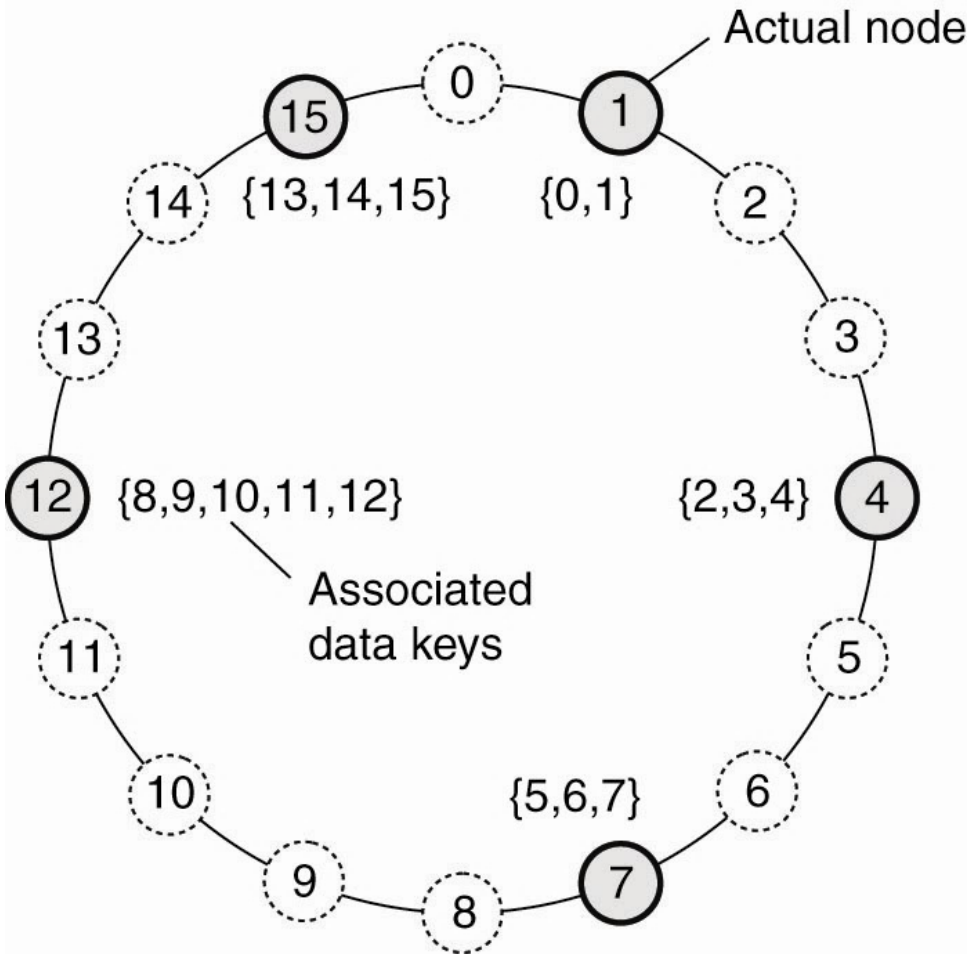
- Chord is a structured peer to peer system which addresses the mentioned concerns

CHORD

- Nodes are logically arranged in a circle
- Intelligence choice of neighbors to reduce the latency and message cost of routing
- Uses consistent hashing on Nodes' addresses
  - Ex. SHA-1(ip,port) -> 160 bit string
  - e.g., a node's key is a hash of its IP address and a file's key might be the hash of its name or of its content or other unique key.
  - The hash function is consistent; which means that keys are distributed evenly across the nodes, with high probability.

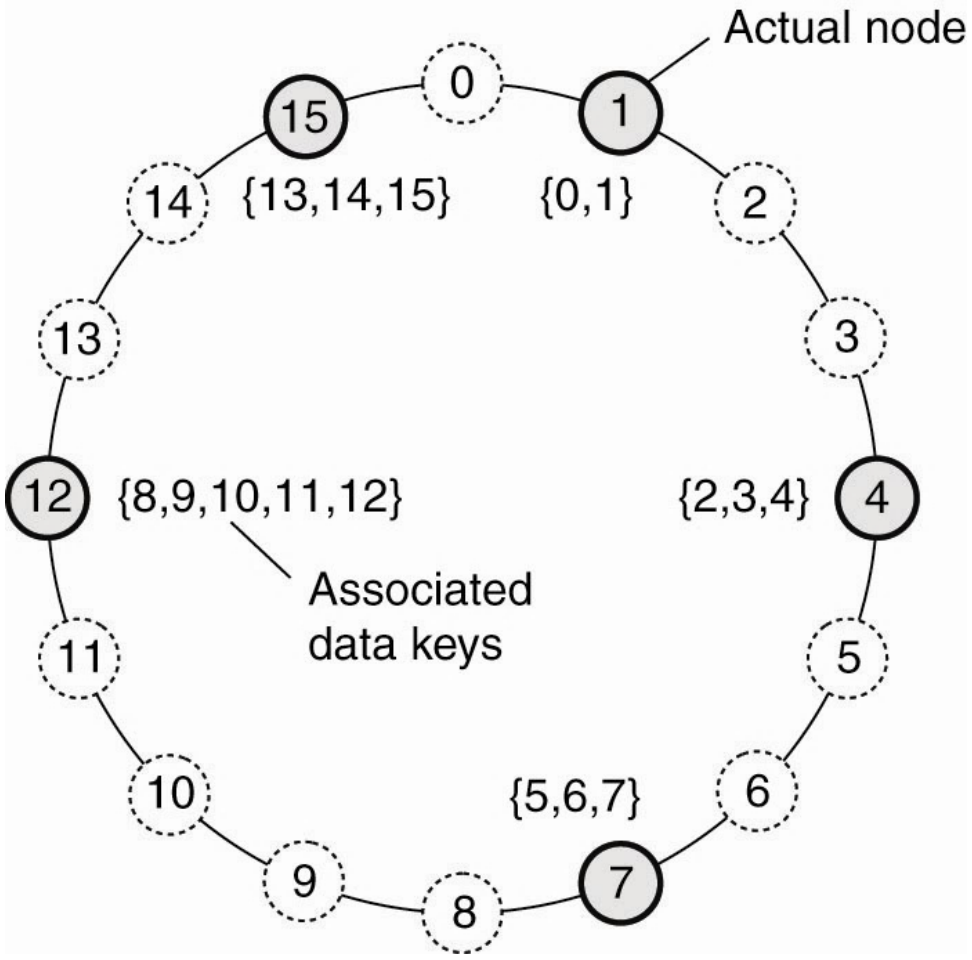
INSERTION IN CHORD

- A data item with key value `k` is mapped to the node with the smallest identifier `id` such that $id \geq k$
- This node is the successor of k, or $succ(k)$
- Modular arithmetic is used



LOOKUP IN CHORD

- Each node in the network knows the location of some fraction of other nodes.
  - If the desired key is stored at one of these nodes, ask for it directly
  - Otherwise, ask one of the nodes you know to look in *its* set of known nodes.
  - The request will propagate through the overlay network until the desired key is located
  - Lookup time is *O(log(N))*

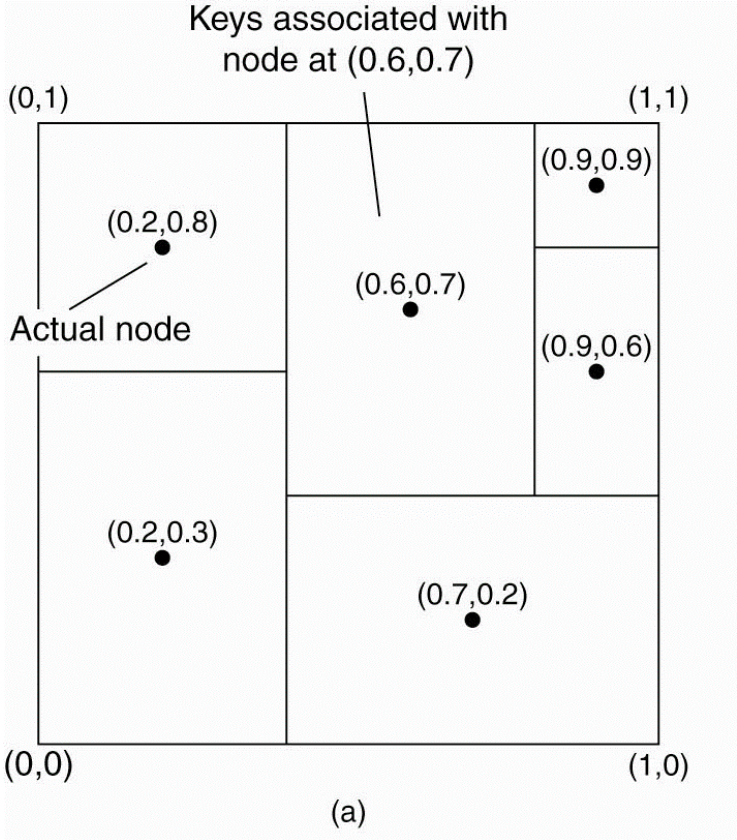


JOINING & LEAVING THE CHORD

- Join
  - Generate the node's random identifier, `id`, using the distributed hash function
  - Use the lookup function to locate `succ(id)`
  - Contact `succ(id)` and its predecessor to insert self into ring.
  - Assume data items from `succ(id)`
- Leave (normally)
  - Notify predecessor & successor;
  - Shift data to `succ(id)`
- Leave (due to failure)
  - Periodically, nodes can run "self-healing" algorithms

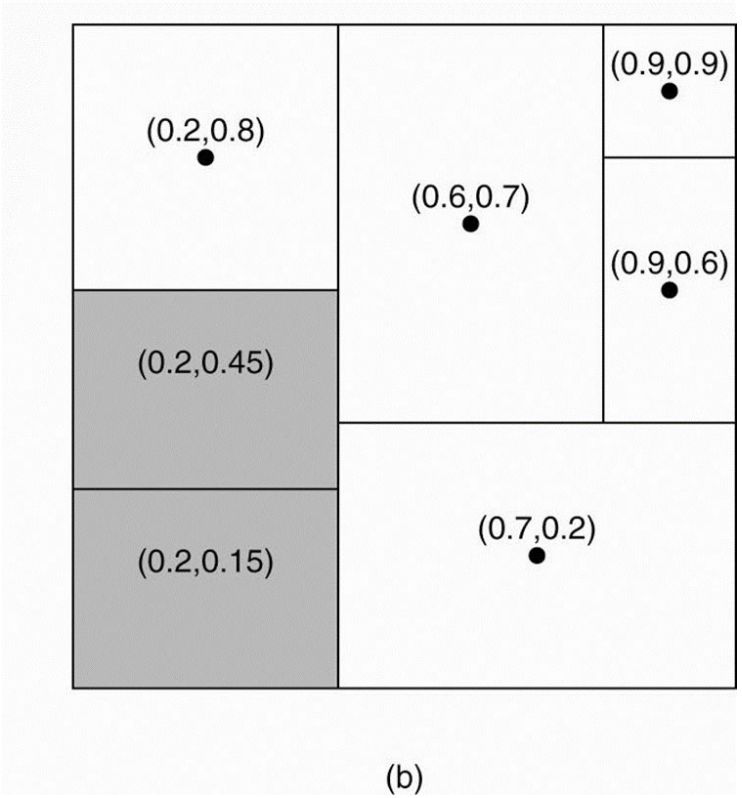
CONTENT ACCESSIBLE NETWORK (CAN)

- 2-dim space [0,1] x [0,1] is divided among 6 nodes
- Each node has an associated region
- Every data item in CAN will be assigned a unique point in space
- A node is responsible for all data elements mapped to its region



CONTENT ACCESSIBLE NETWORK (CAN)

- To add a new region, split the region
- To remove an existing region, neighbor will take over



STRUCTURED P2P SUMMARY

- Deterministic: If an item is in the system it will be found
- No need to know where an item is stored
- Lookup operations are relatively efficient
- DHT-based P2P systems scale well

UNSTRUCTURED P2P ARCHITECTURE

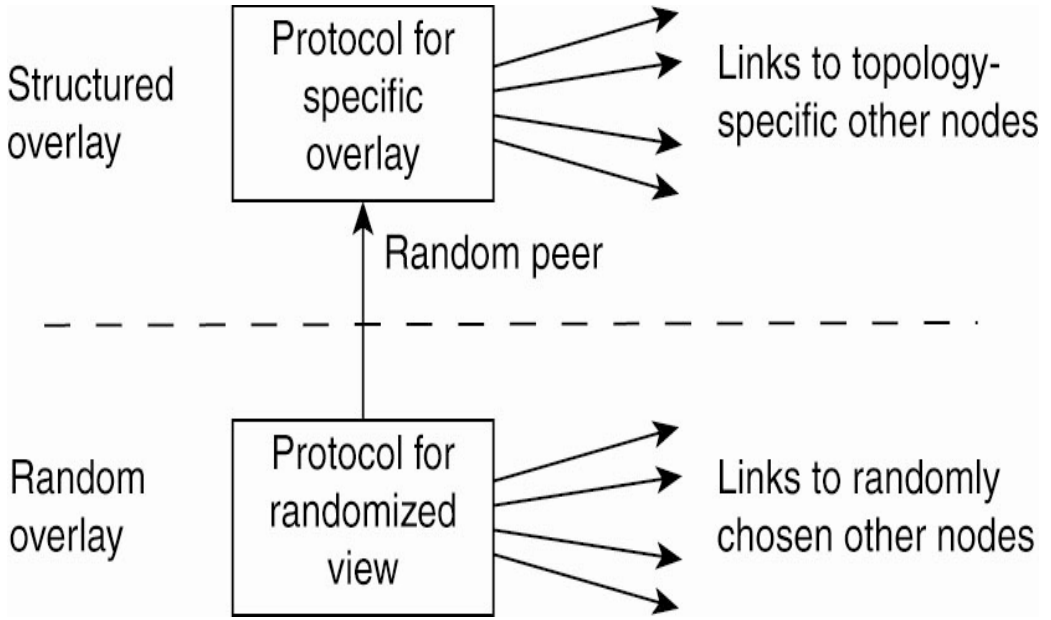
- Largely relying on randomized algorithm to construct the overlay network
  - Each node has a list of neighbors, which is more or less constructed in a random way
- One challenge is how to efficiently locate a needed data item
  - Flood the network?
- Many systems try to construct an overly network that resembles a random graph
  - Each node maintains a ***partial view***, i.e., a set of live nodes randomly chosen from the current set of nodes

PARTIAL VIEW CONSTRUCTION

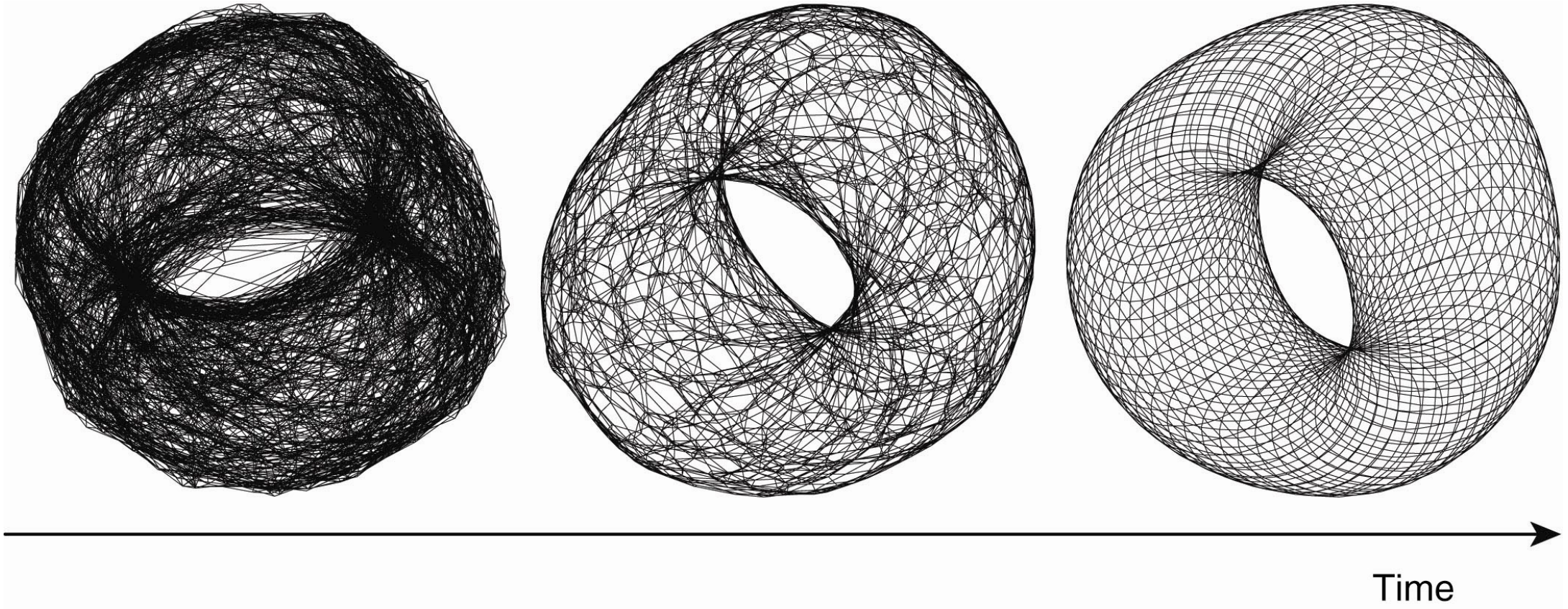
- Nodes exchange entries from their partial view regularly
  - Each entry is associated with an age tag
- Consists of an active thread and a passive thread
  - The active thread initiate the communication with a selected peer for partial view propagation
  - The passive thread waits for response from another peer and update its partial view accordingly
  - A node can be in PUSH mode or PULL mode

TOPOLOGY MANAGEMENT

- Some specific topologies may benefit the applications in a given P2P system
  - E.g., only including nearest peers in the partial view may reduce the latency of data delivery
- How to constructing a specific topology from a unstructured P2P systems
- Solution: two-layered approach
  - Lower layer: unstructured P2P outputs a random graph
  - Higher layer: carefully exchange and selecting entries to build a desired topology



TOPOLOGY MANAGEMENT

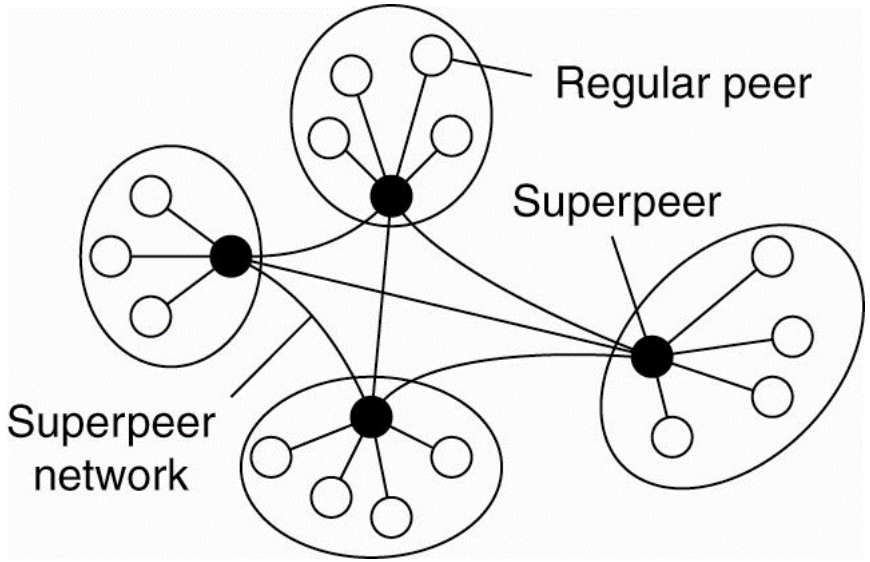


FINDING DATA ITEMS

- This is quite challenging in unstructured P2P systems
  - Assume a data item is randomly placed
- Solution 1: Flood the network with a search query
- Solution 2: A randomized algorithm
  - Let us first assume that
- Each node knows the IDs of k other randomly selected nodes
- The ID of the hosting node is kept at m randomly picked nodes
  - The search is done as follows
- Contact k direct neighbors for data items
- Ask your neighbors to help if none of them knows
  - What is the probability of finding the answer directly?

SUPERPEERS

- Maintain indexes to some or all nodes in the system
- Supports resource discovery
- Act as servers to regular peer nodes, peers to other superpeers
- Improve scalability by controlling floods
- Can also monitor state of network
- Example: Napster

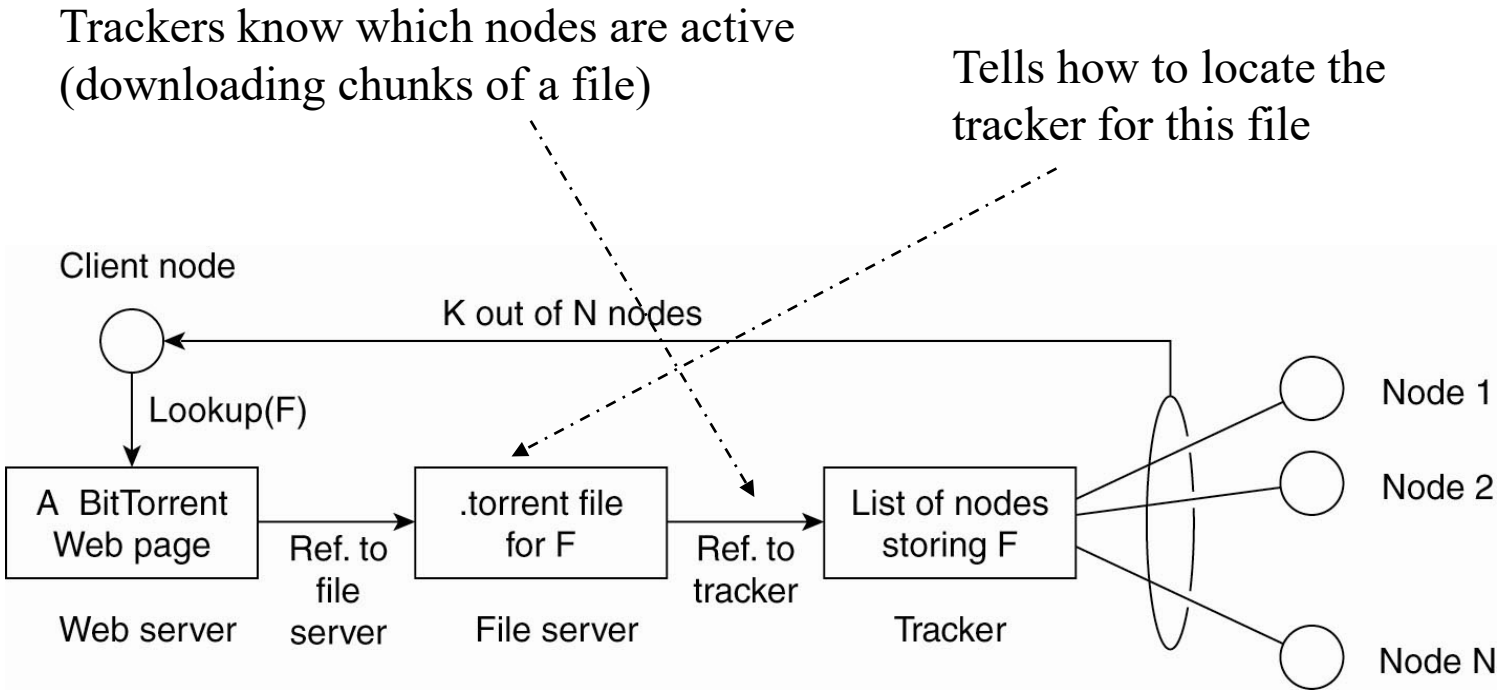


HYBRID ARCHITECTURES

- Combine client-server and P2P architectures
  - Edge-server systems; e.g. ISPs, which act as servers to their clients, but cooperate with other edge servers to host shared content
  - Collaborative distributed systems; e.g., BitTorrent, which supports parallel downloading and uploading of chunks of a file. First, interact with C/S system, then operate in decentralized manner.
- Many real distributed systems combine architectural features
  - E.g., the superpeer networks – combine client-server architecture (centralized) with peer-to-peer architecture (decentralized)
- Two examples of hybrid architectures
  - Edge-server systems
  - Collaborative distributed systems

COLLABORATIVE DISTRIBUTED SYSTEMS (BIT TORRENT)

- Designed to force users of file-sharing systems to participate in sharing.
- Simplifies the process of publishing large files, e.g. games
- When a user downloads your file, he becomes in turn a server who can upload the file to other requesters.
- Share the load – doesn't swamp your server



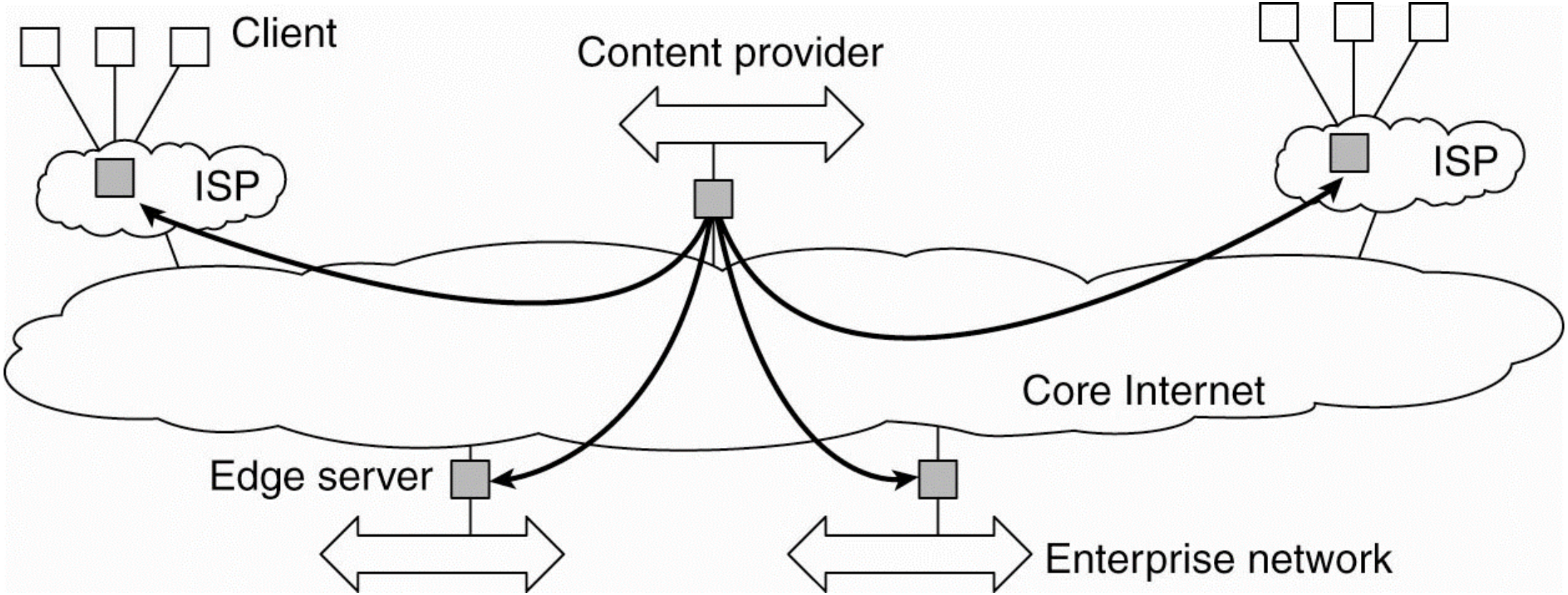
GLOBULE

- Collaborative content distribution network:
  - Similar to edge-server systems
  - Enhanced web servers from various users that replicates web pages
- Components
  - A component that can redirect client requests to other servers.
  - A component for analyzing access patterns.
  - A component for managing the replication of Web pages.
- Has a centralized component for registering the servers and make these servers known to others

GLOBULE

- Example:
  - Alice has a web server; Bob has a web server
  - Alice's server can have replicated contents of the Bob's server and vice versa
- Good if your server goes down
- Good if too much traffic that your server can not handle or gets too slow
- Better Geographic diversity
  - Allow users to get quick response from the nearest server with the replicated page

EDGE-SERVER SYSTEMS



ARCHITECTURE VERSUS MIDDLEWARE

Middleware: the software layer between user applications and distributed platforms.

Purpose: to provide distribution transparency

Applications can access programs running on remote nodes without understanding the remote environment

Many middleware follows a specific architecture style

Object-based style, event-based style

Benefits: simpler to design application

Limitations: the solution may not be optimal

Should be adaptable to application requirements

Separating policies from mechanism 36

ARCHITECTURE VERSUS MIDDLEWARE

Middleware may also have an architecture

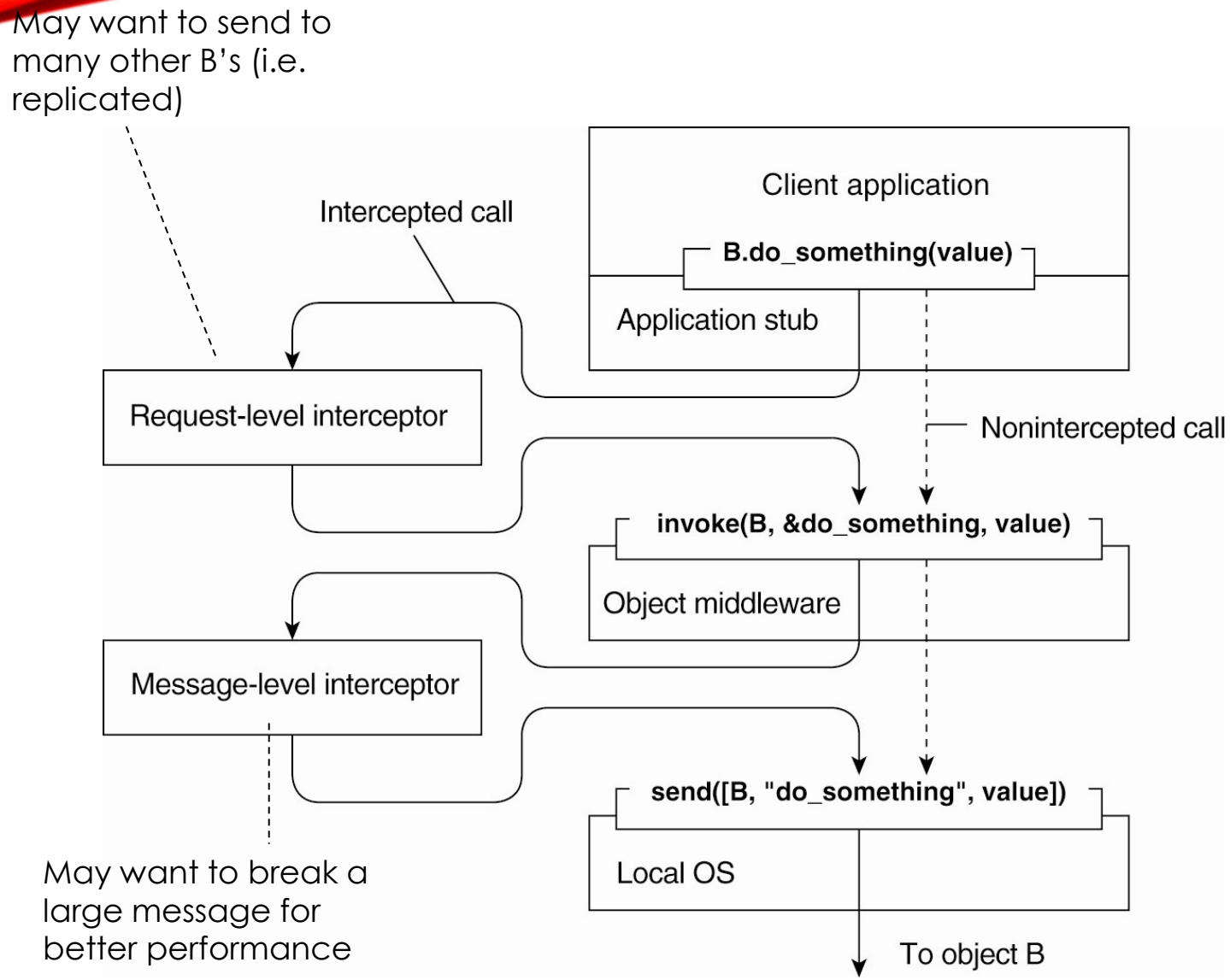
- e.g., CORBA has an object-oriented style.

Use of a specific architectural style can make it easier to develop applications, but it may also lead to a less flexible system.

Possible solution: develop middleware that can be customized as needed for different applications.

INTERCEPTORS

- An Interceptor is a software that
  - breaks the usual flow of control and
  - allows other (application specific) code to be executed
- It makes middleware more adaptable to
  - application requirements and changing environment
- Interceptors are good for
  - providing transparent replication and
  - improving performance



GENERAL APPROACHES FOR ADAPTABILITY

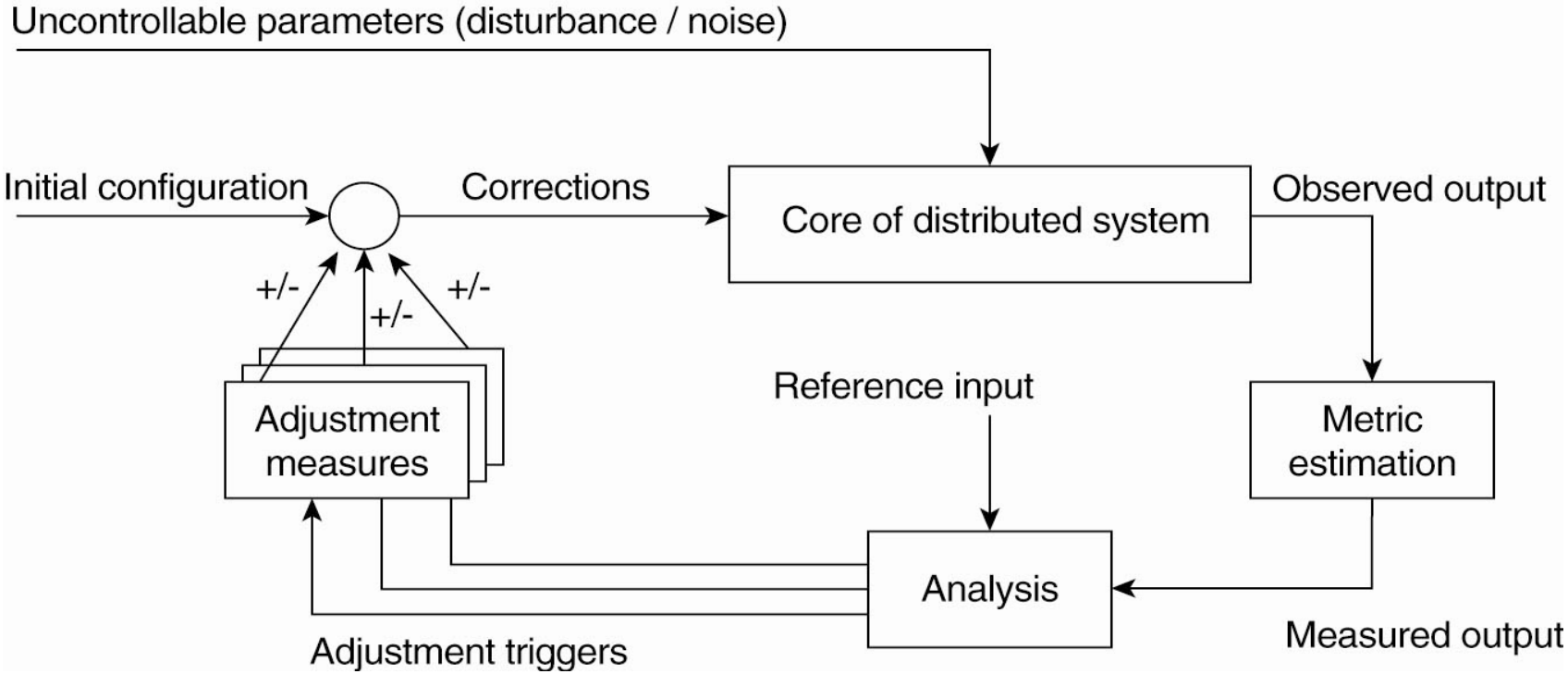
- Separation of concerns:
  - Modularizing the system and separate security from functionality
  - However, the problem is that a lot of things you cannot easily separate, e.g., security
- Computational reflection
  - Ability to inspect itself, and if necessary, adapt its behavior
  - Reflective middleware has yet to proof itself as a powerful tool to manage the complexity of distribute systems
- Component-based design
  - However, components are less independent than one may think
  - Replacement of one component may have huge impact on others

SELF-MANAGEMENT IN DISTRIBUTED SYS.

- Distributed systems are often required to adapt to environmental changes by
  - switching policies for allocation resources
- The algorithms to make the changes are often already in the components
  - But the challenge is how to make such change without human intervention
- A strong interplay between software architectures and system architectures
  - Organize components in a way that monitoring and adjustment can be done easily
  - Decide where the processes to be executed to do the adaption

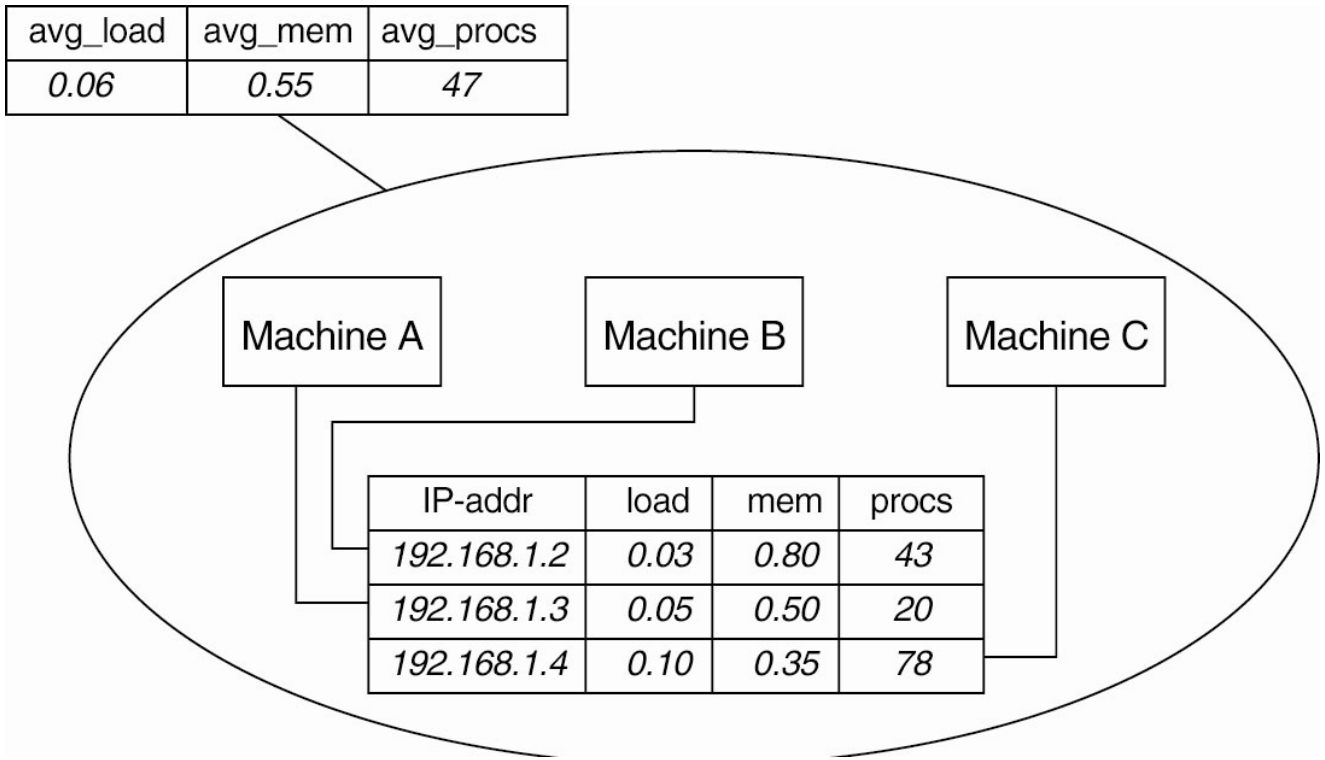
THE FEEDBACK CONTROL SYSTEMS

- Allow automatic adaption to changes by means of one or more feedback control loops
  - self-managing, self-healing, self-configuration, self-optimization, etc.



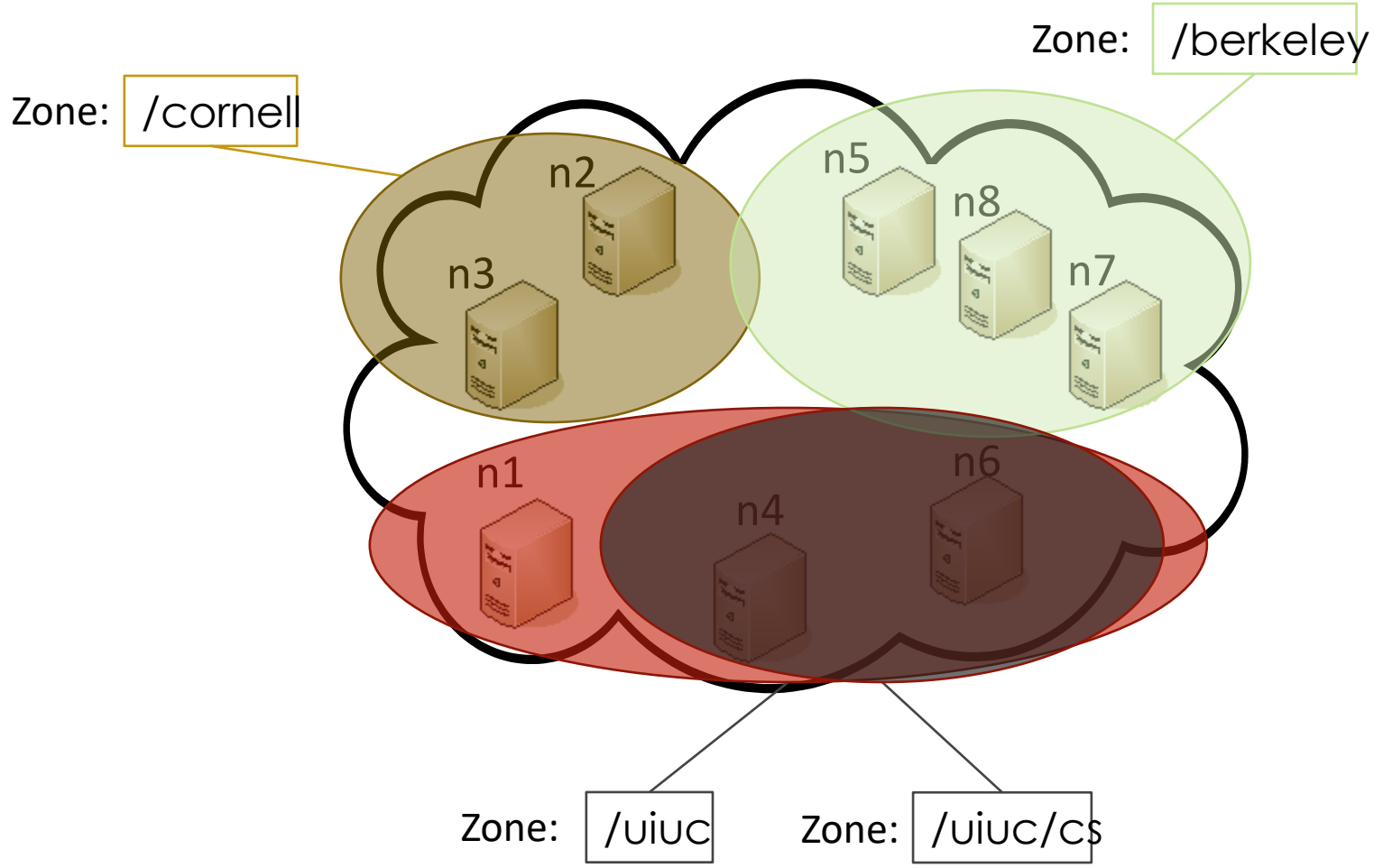
SYSTEM MONITORING WITH ASTROLABE

- A tool for observing system behavior in a distributed system
  - One component of the feedback control system
- Every host runs a Astrolabe process, called an agent
  - Agents are organized as a hierarchy zones



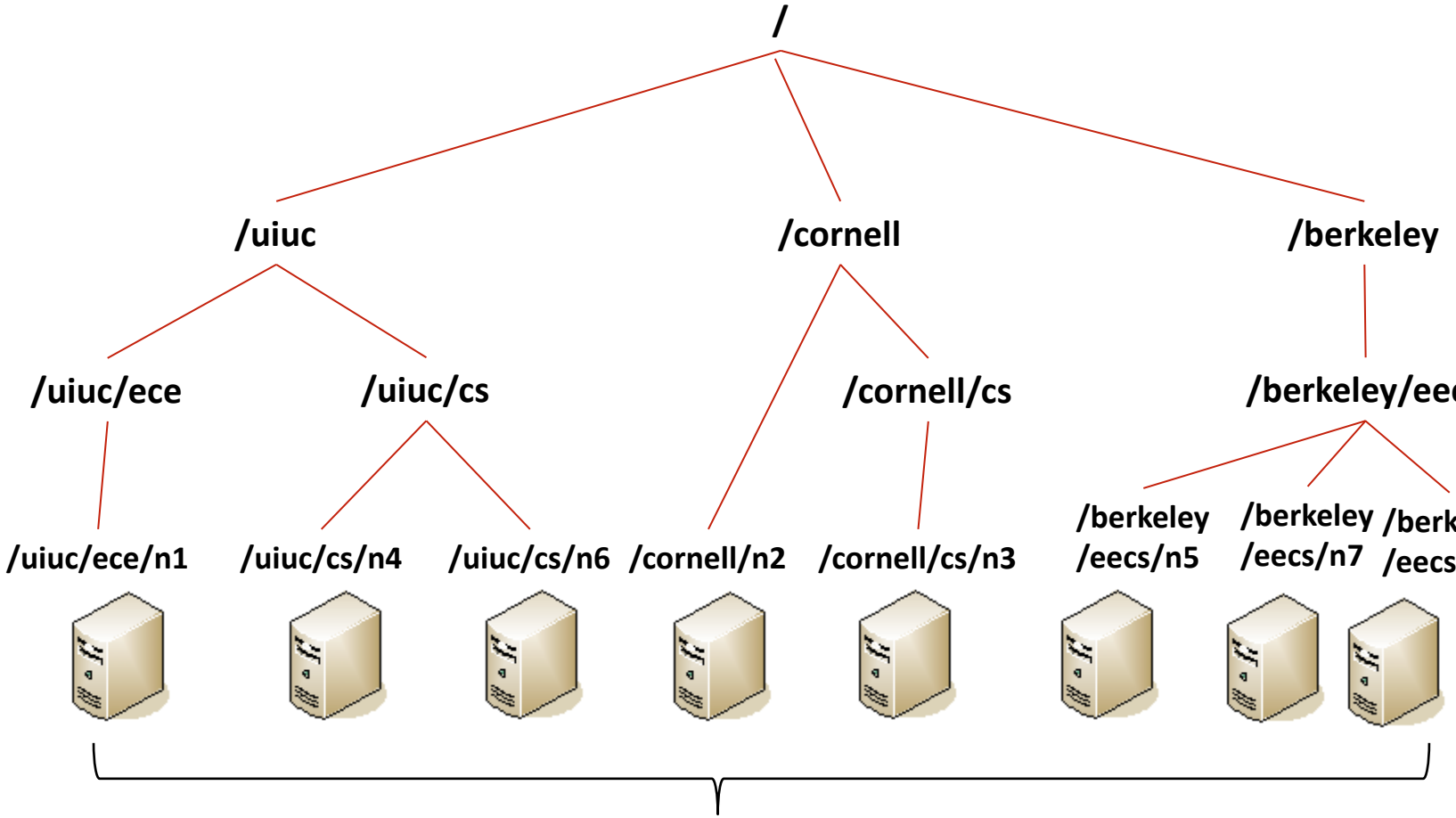
SYSTEM MONITORING WITH ASTROLABE

- A tool for observing system behavior in a distributed system
  - One component of the feedback control system
- Every host runs a Astrolabe process, called an agent
  - Agents are organized as a hierarchy zones



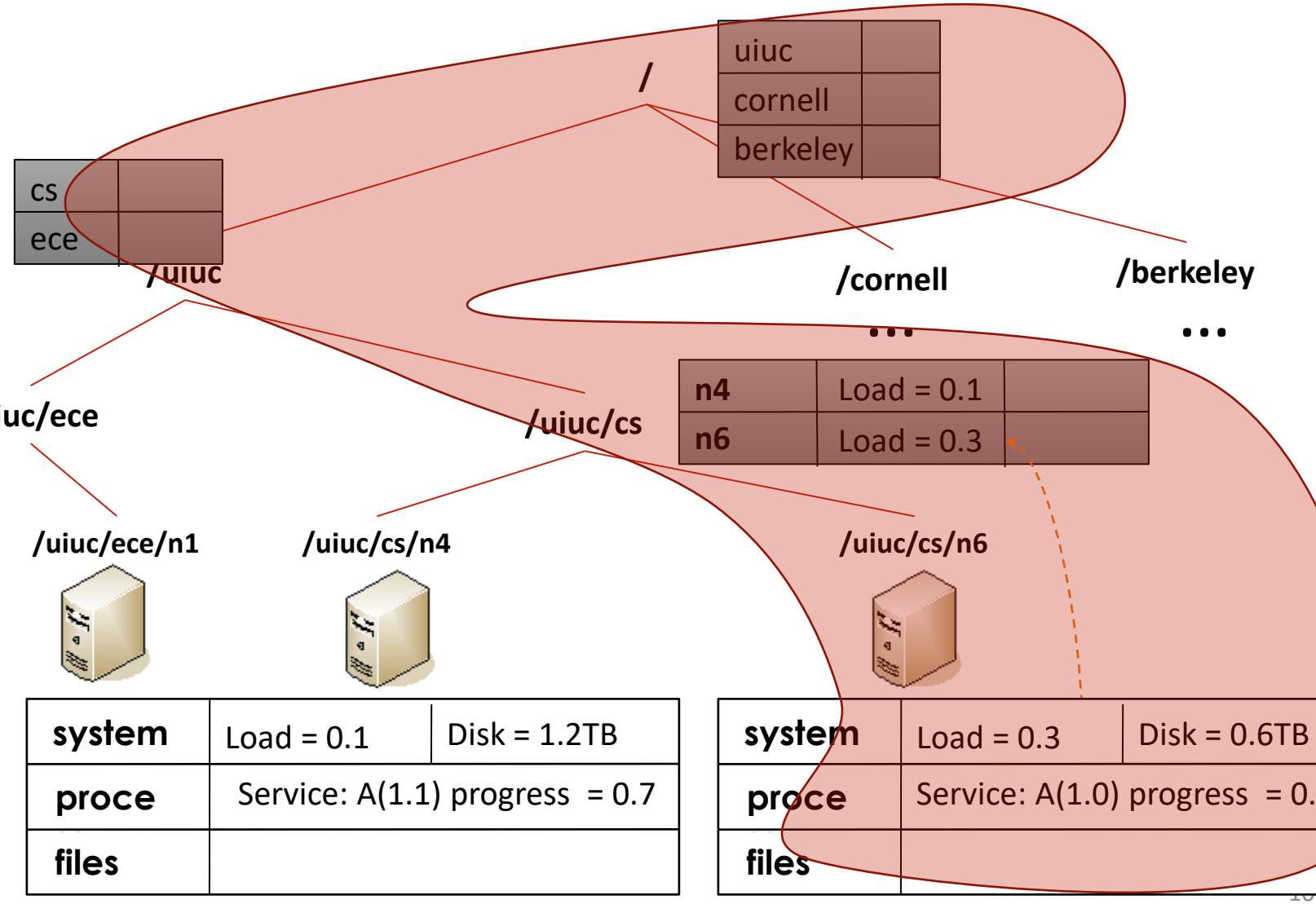
SYSTEM MONITORING WITH ASTROLABE

- Zone hierarchy is determined by the administrators (less flexibility).
- Assumption: zone names are consistent with the physical topology.



SYSTEM MONITORING WITH ASTROLABE

- Agent (/uiuc/cs/n6) has its local copy of
- these management table of MIBs.



STATE AGGREGATION