PRINCE SULTAN UNIVERSITY

جامعة الامير سلطان

CS435 Distributed systems

DISTRIBUTED SYSTEMS ARCHITECTURE

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TOPICS

- Operating Systems, a quick review
- Distributed Systems Themes
- Dist. Sys. Challenges
- Dist. Sys. Architecture
- Distributed Services

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OPERATING SYSTEMS

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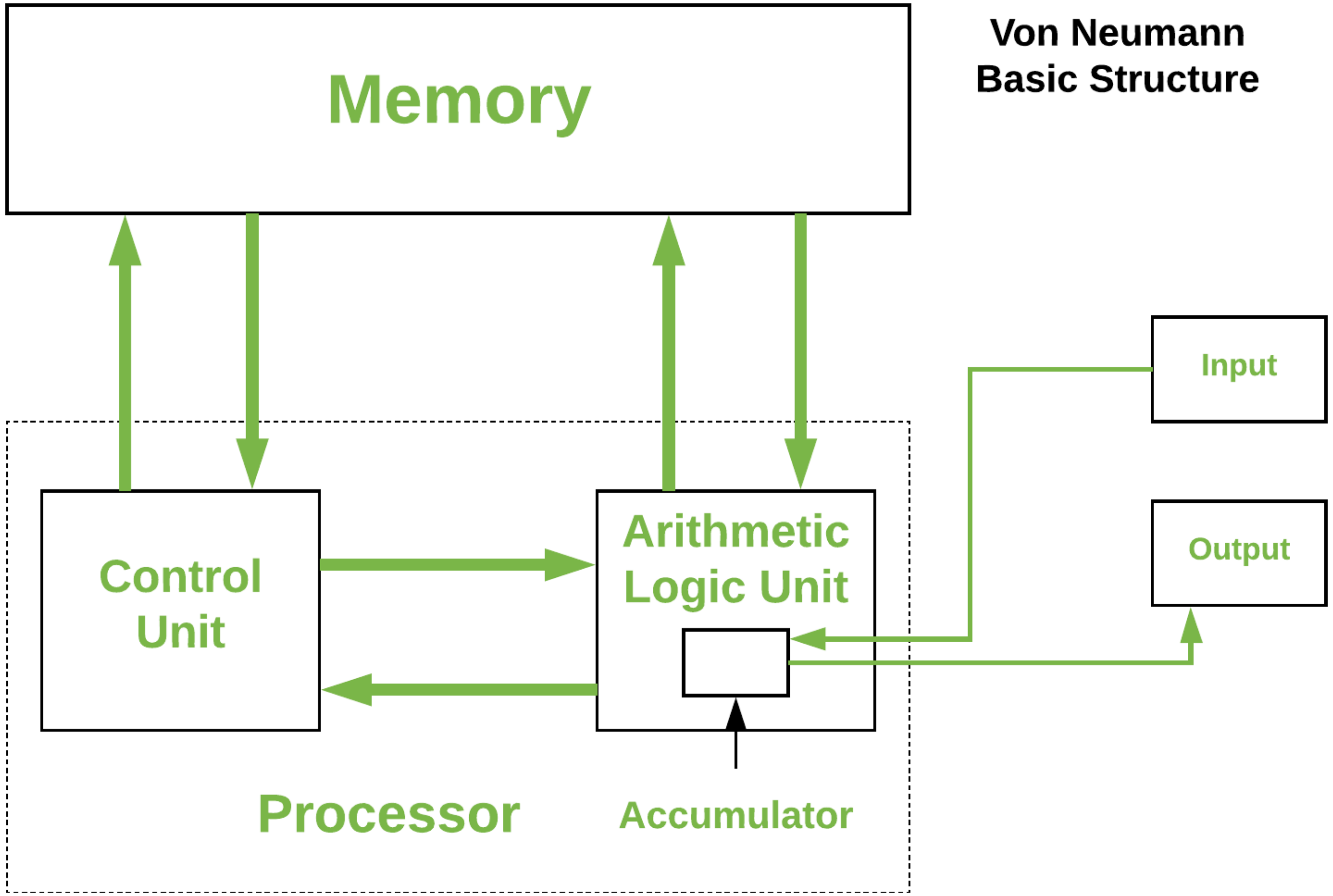
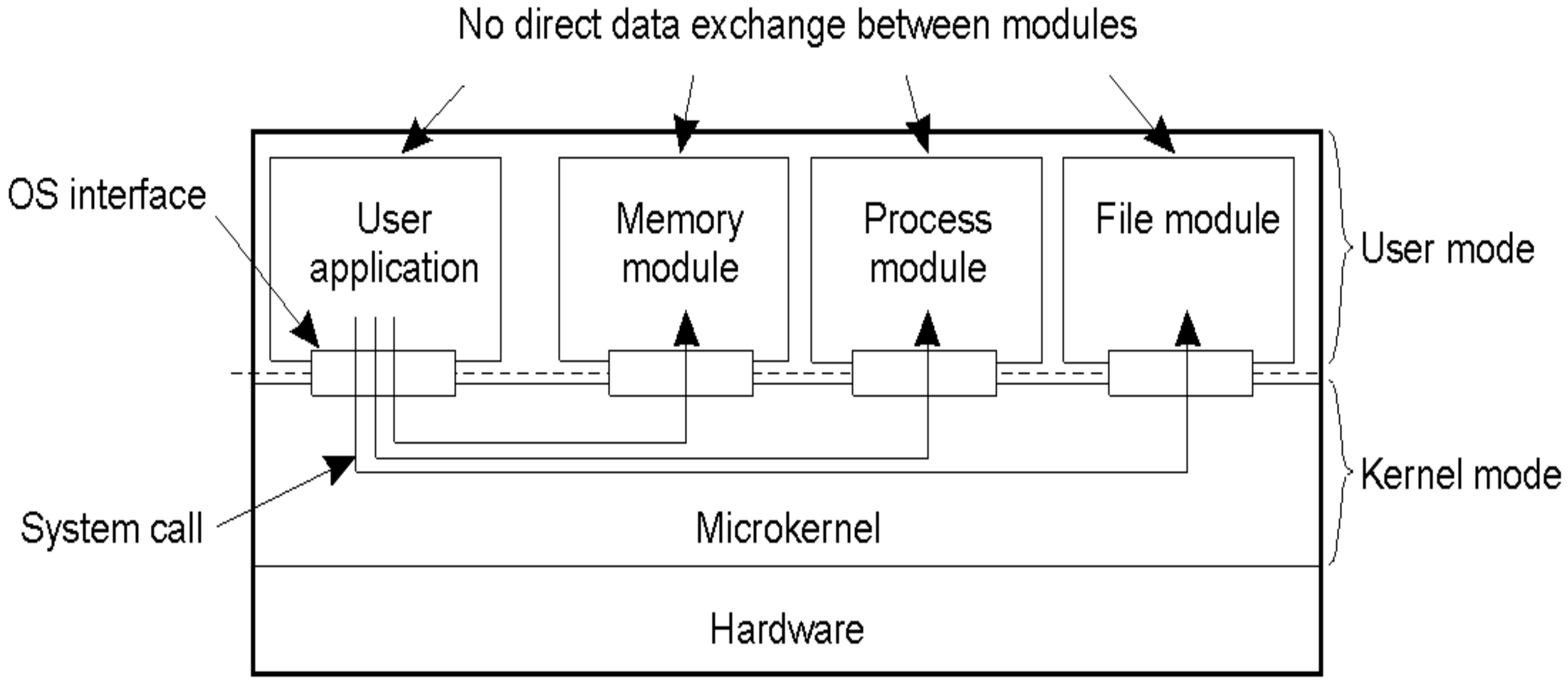
OPERATING SYSTEMS, A QUICK REVIEW

- Computer Organization



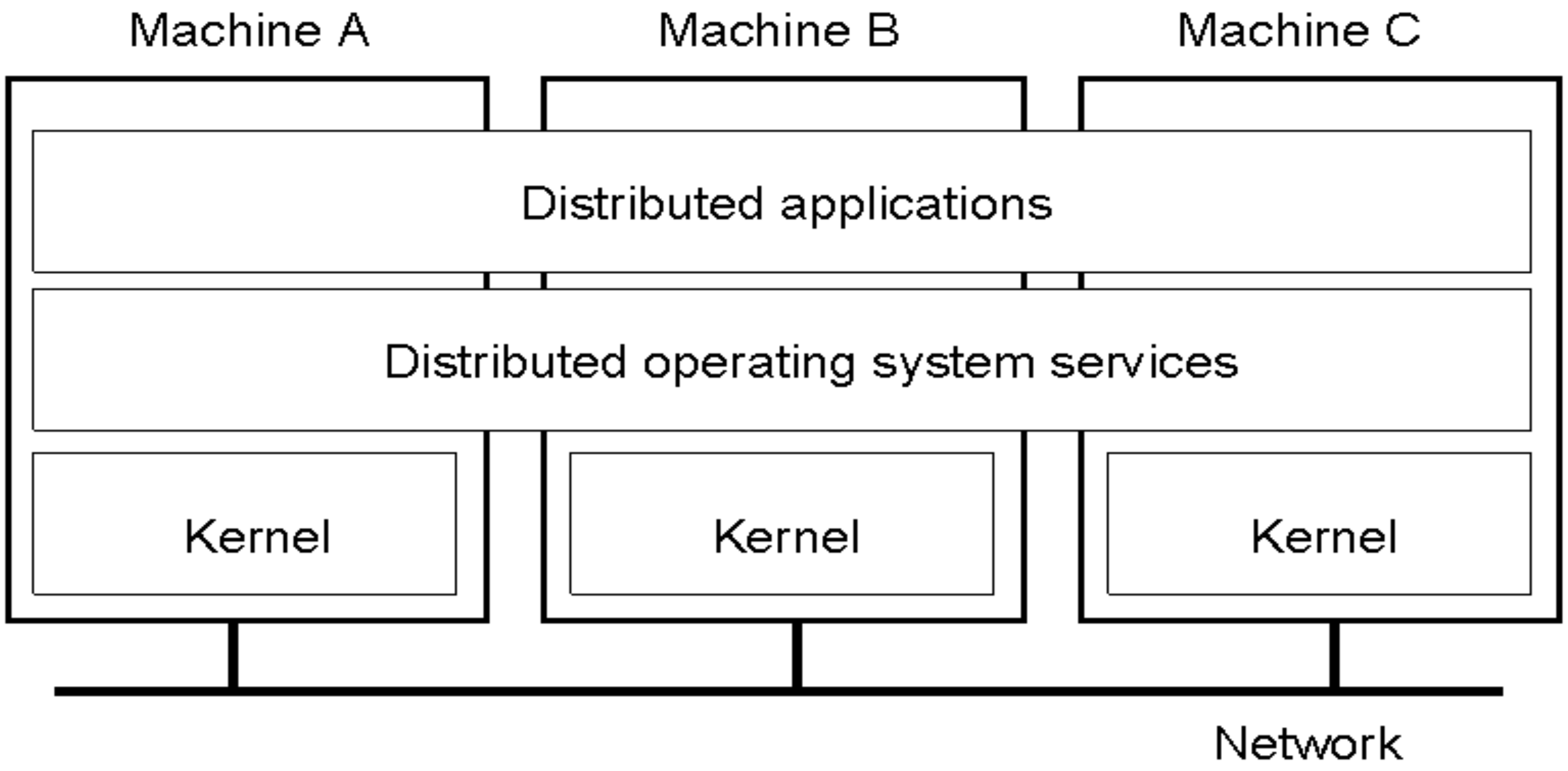
OPERATING SYSTEMS, A QUICK REVIEW

- Uni-Computer Operating Systems
  - Application, Memory, Processor, File-system resources, all on one machine



OPERATING SYSTEMS, A QUICK REVIEW

- Multi-Computer Operating System
  - All computers run using the same OS.
  - Memory shared between processors.
  - Dist. Applications run sharing Memory and CPU resources



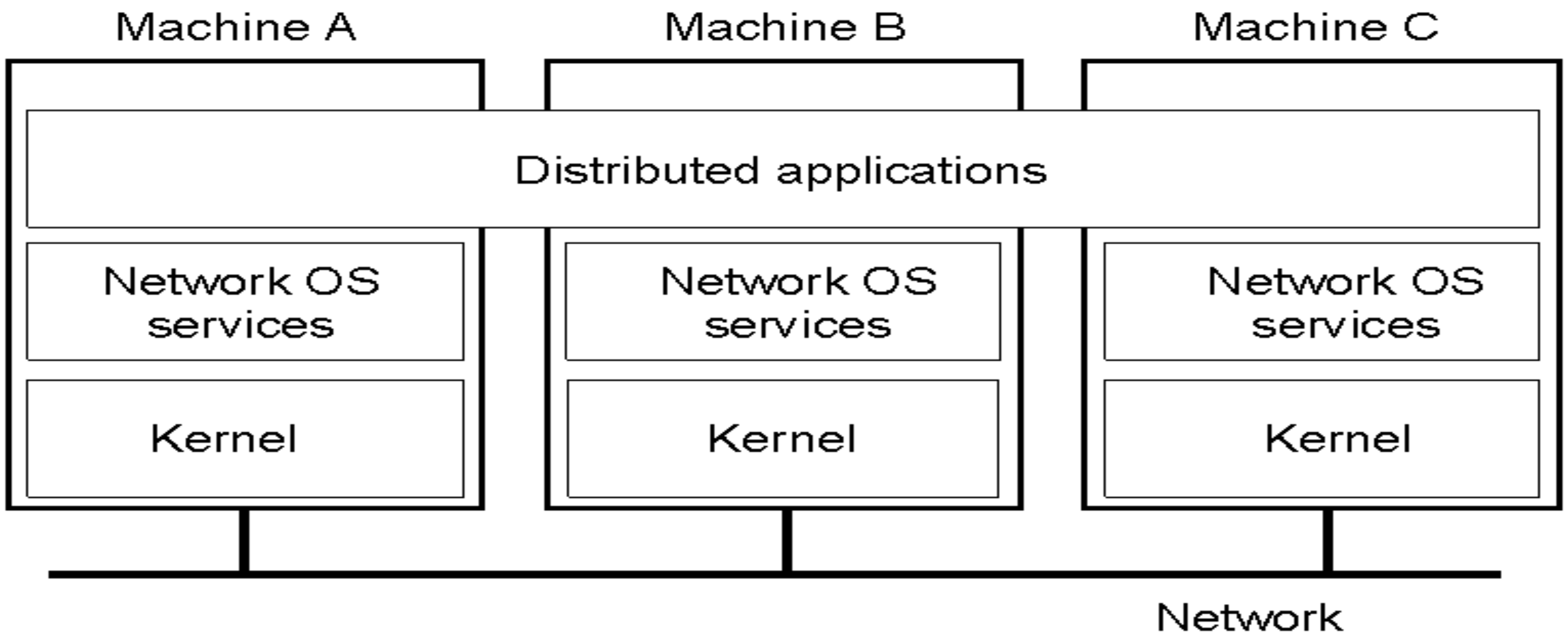
Linux

VMware ESXi™

The original BSD daemon appeared first in 1983 on the cover of the 4.2BSD manuals published by the Usenix Association

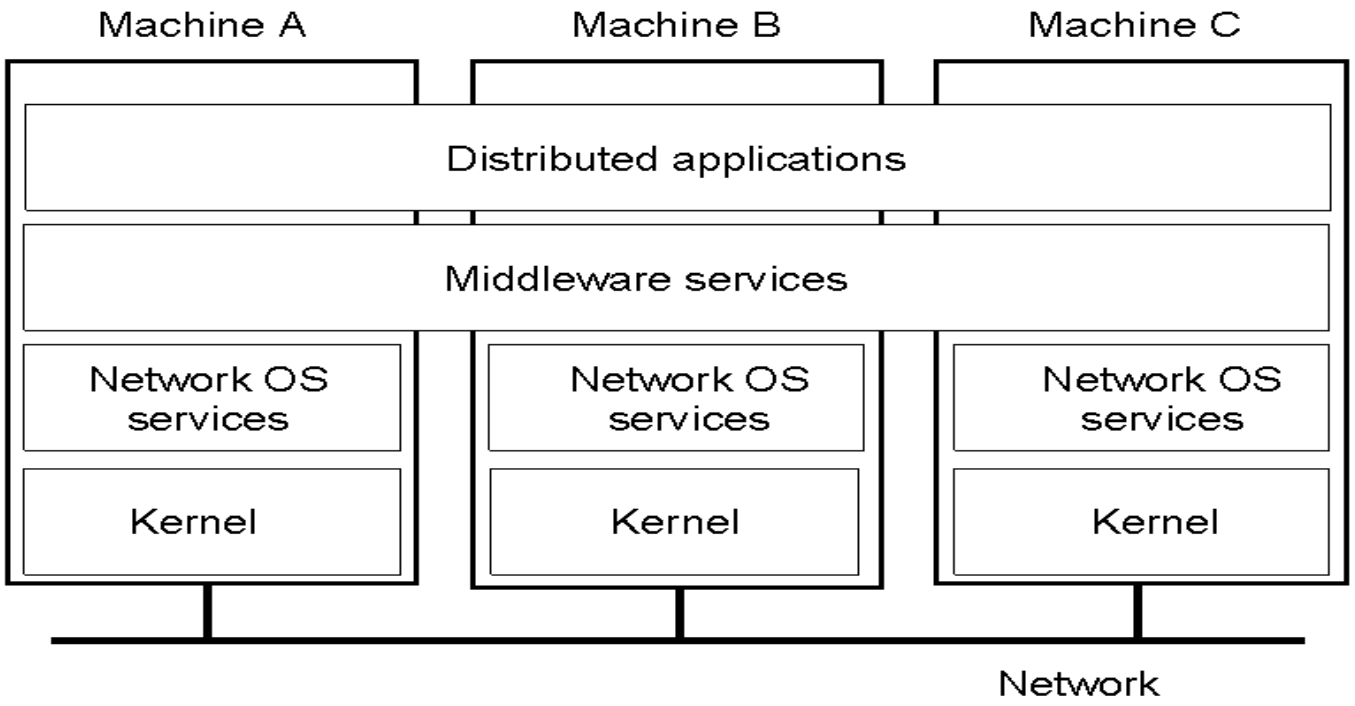
OPERATING SYSTEMS, A QUICK REVIEW

- Network Operating Systems
  - Network File system mounting on individual machines.
  - Resources accessible via network.
  - Relatively primitive set of services provided (e.g. Printers)
  - Hard to maintain a consistent view. Configuration overhead/complexity



OPERATING SYSTEMS, A QUICK REVIEW

- Middleware-based Operating Systems
  - Middleware provides a set of services and communication protocols
  - Abstracts the complexities of distributed computing, making it easier for developers to design and implement distributed applications. E.g. Socket APIs



OPERATING SYSTEMS, A QUICK REVIEW

- Comparing Operating Systems

Item	**Distributed OS**		**Network OS**	**Middleware-based OS**
	Multiproc.	**Multicomp.**		
Degree of transparency	Very High	High	Low	High
Same OS on all nodes	Yes	Yes	No	No
Number of copies of OS	1	N	N	N
Basis for communication	Shared memory	Messages	Files	Model specific
Resource management	Global, central	Global, distributed	Per node	Per node
Scalability	No	Moderately	Yes	Varies
Openness	Closed	Closed	Open	Open

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DISTRIBUTED SYSTEMS THEMES

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DISTRIBUTED SYSTEM THEMES

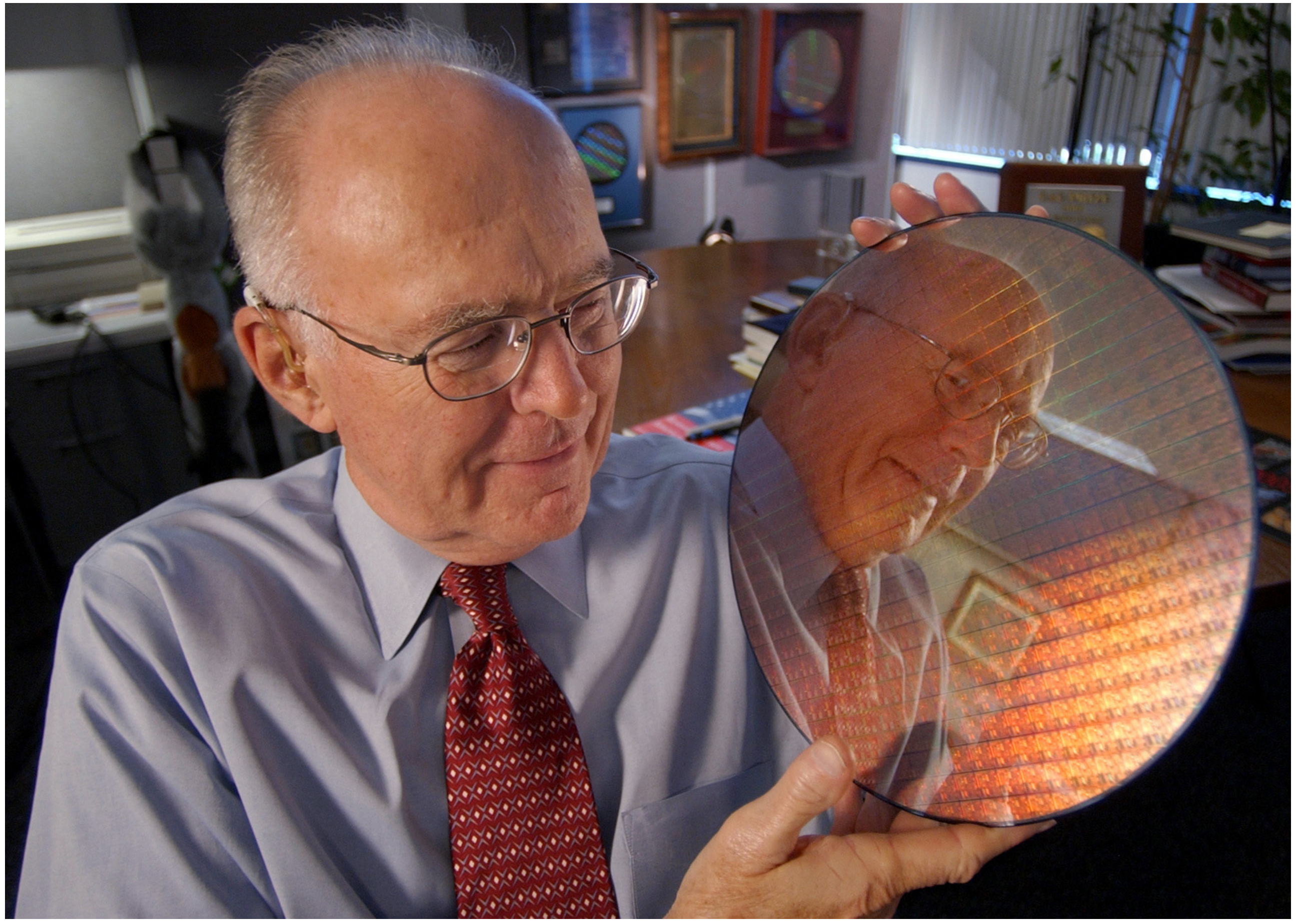
- Distributed Systems are a collection of independent computers that appears as a single system to the user(s)
  - **Independent** = autonomous, self-contained
  - **Single system** = user not aware of distribution
- Relevant terms / themes
  1. Scaling
  2. Collaboration
  3. Latency
  4. Acessibility
  5. Availability
  6. Transparency

1. SCALING

- **Vertical Scaling (Powerful systems)**

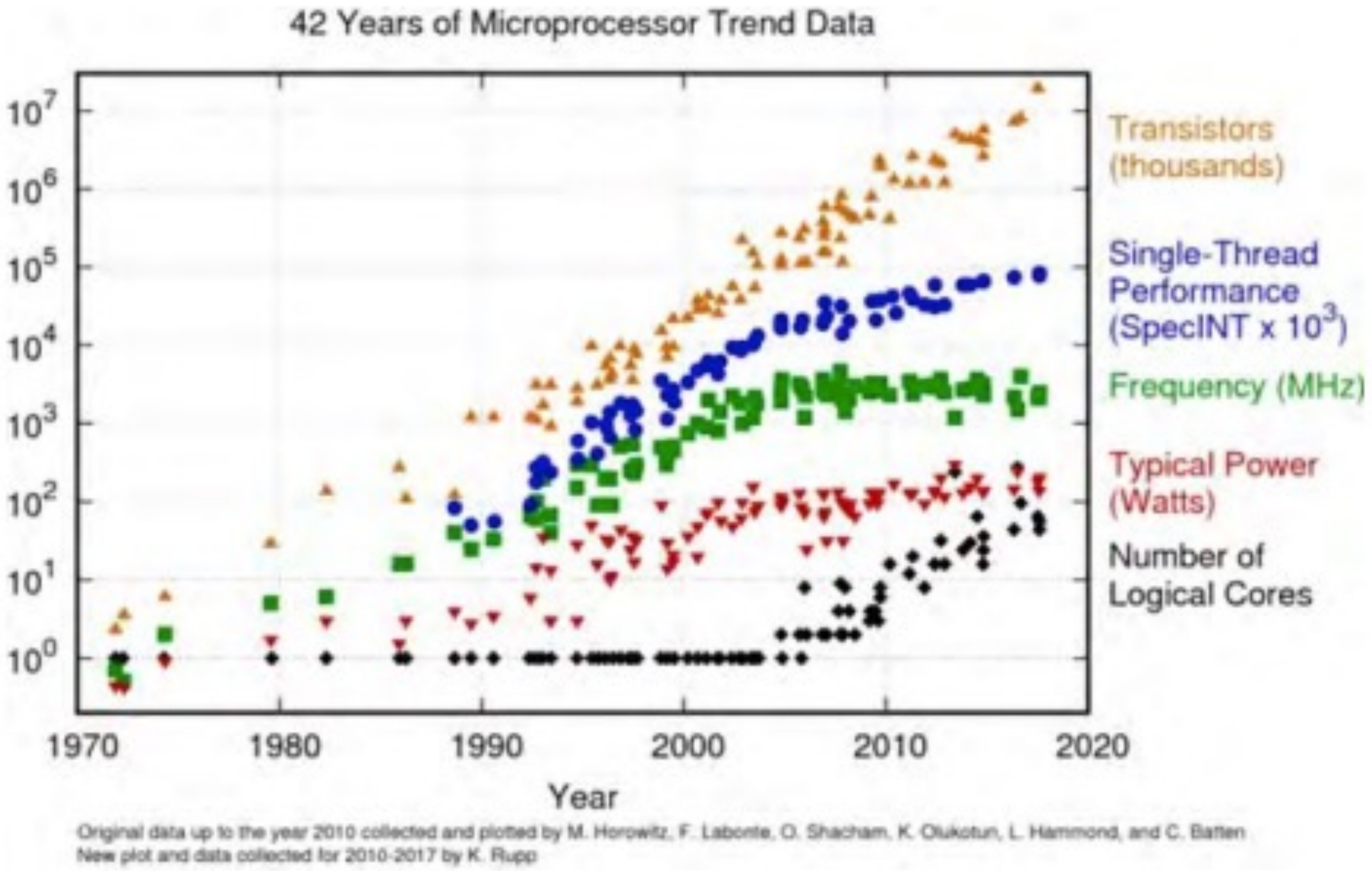
Moore's law

"The number of transistors on a microchip doubles approximately every two years, while the cost of computers is halved"



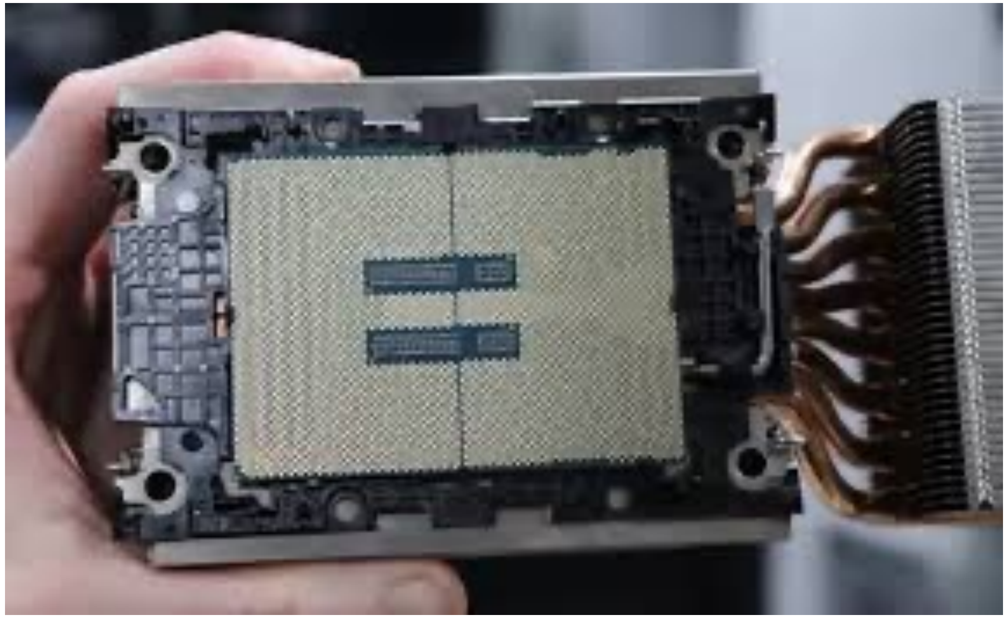
1. SCALING

- Vertical Scaling (Powerful systems)
    - Increases in processor performance <u>have not been keeping up with Moore's Law since around 2005</u>.



1. SCALING

- Vertical Scaling (Powerful systems)
  - Adding more processor cores helped improve performance; but need to **write multi-threaded programs**
    - Intel Xeon 8490h 1.90GHz~3.50GHz **60Core**/120Thread Processor (15000 USD)
    - Apple M3 Ultra 32-core CPU/ **80 Core** GPU
    - Nvidia Geforce RTX 4090 **18,432** CUDA **cores**



1. SCALING

- Horizontal Scaling
  - **<u>Distributed load across more systems</u>**
    - Pixar Movie Rendering: 2000 machines with 24000+ cores used to render frames.
    - Google: A single Google query uses 1,000 computers in 0.2 seconds to retrieve an answer

2. COLLABORATION

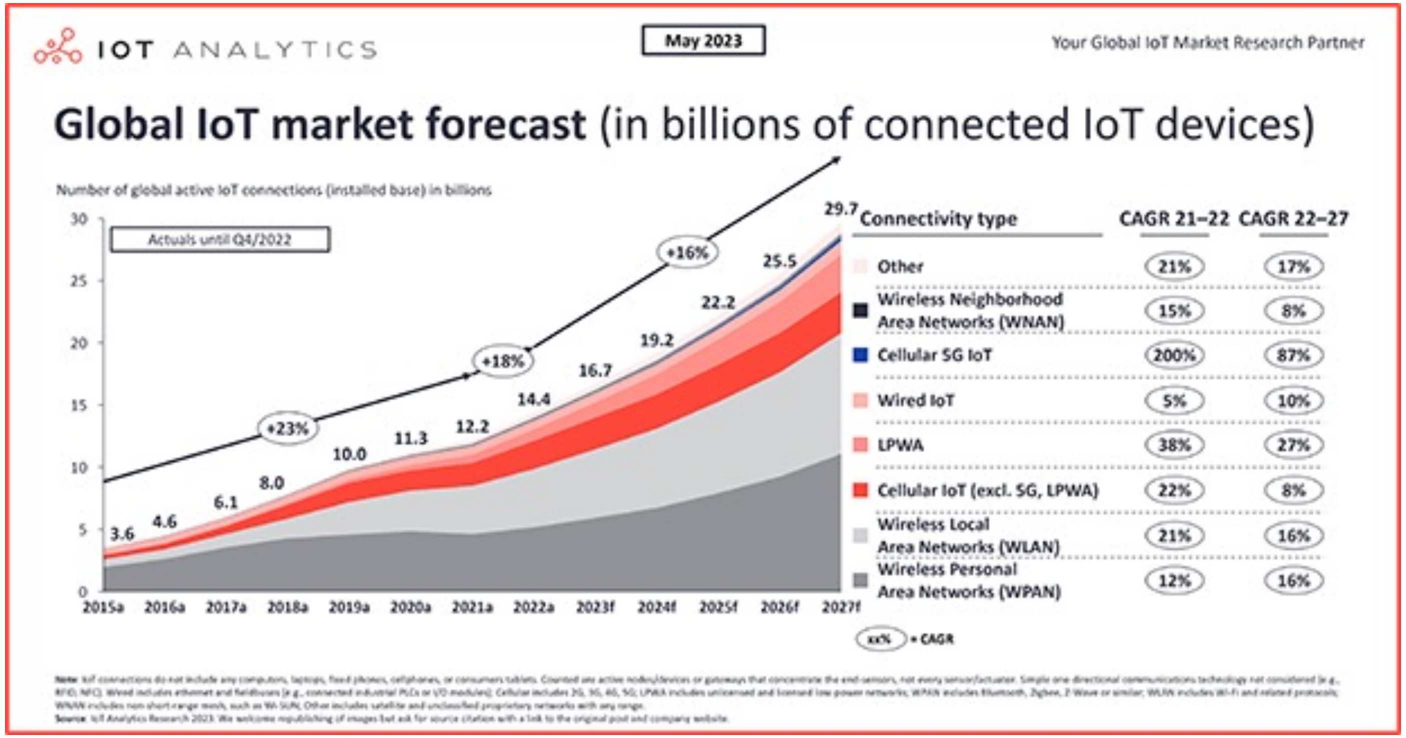
- Collaborate
  - Make content
  - Social connectivity
  - E-Commerce
  - News & media

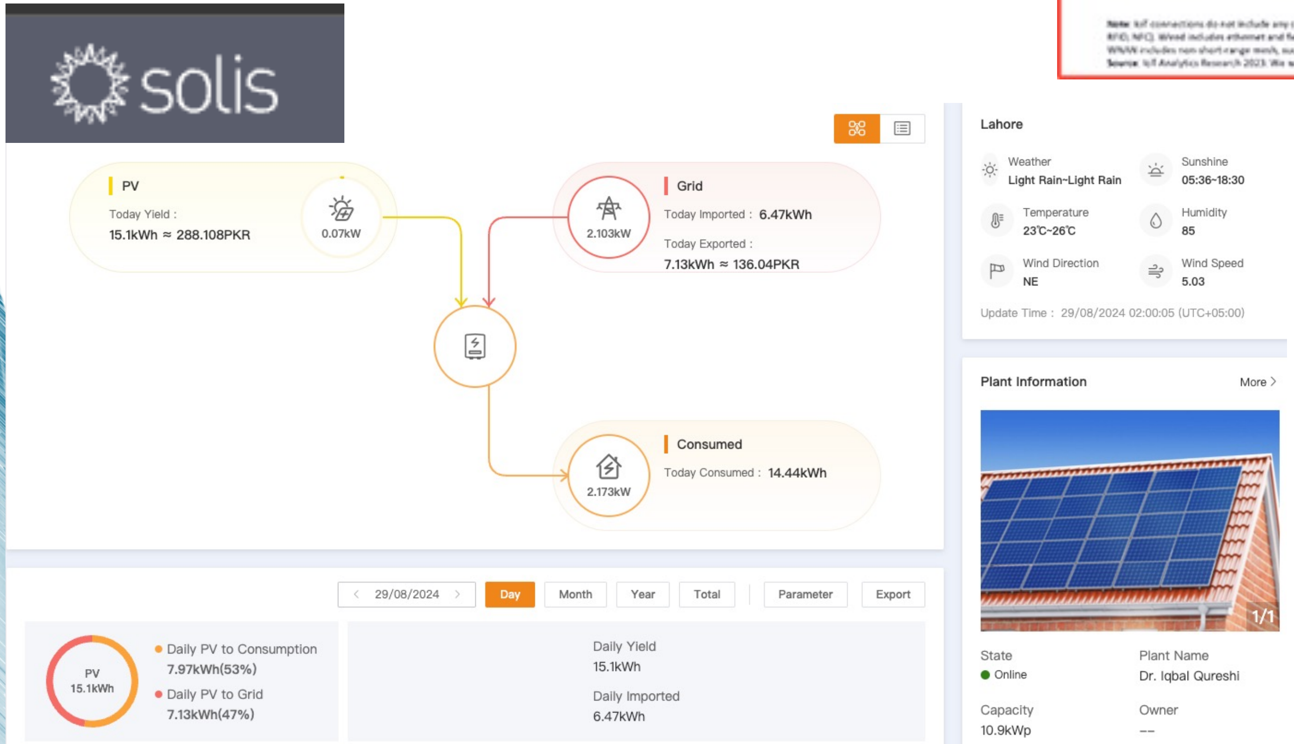
3. LATENCY

- **Caching**
  - Keep the data close to where it is needed
- **Replication**
  - Make multiple copies
- *Caching vs. replication*
  - Caching: temporary copies of frequently accessed data closer to where it’s needed
  - Replication: multiple copies of data for increased fault tolerance

4. ACCESSIBILITY

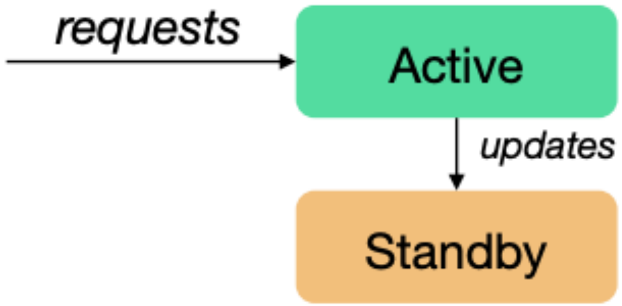
- Distributed Systems are accessible through Systems, IoT devices, Smart-phones etc.
- IoT = Internet of Things
  - 2023: 16.7 Billion devices
- Smart-Phones
  - 2023: 6.2 Billion devices

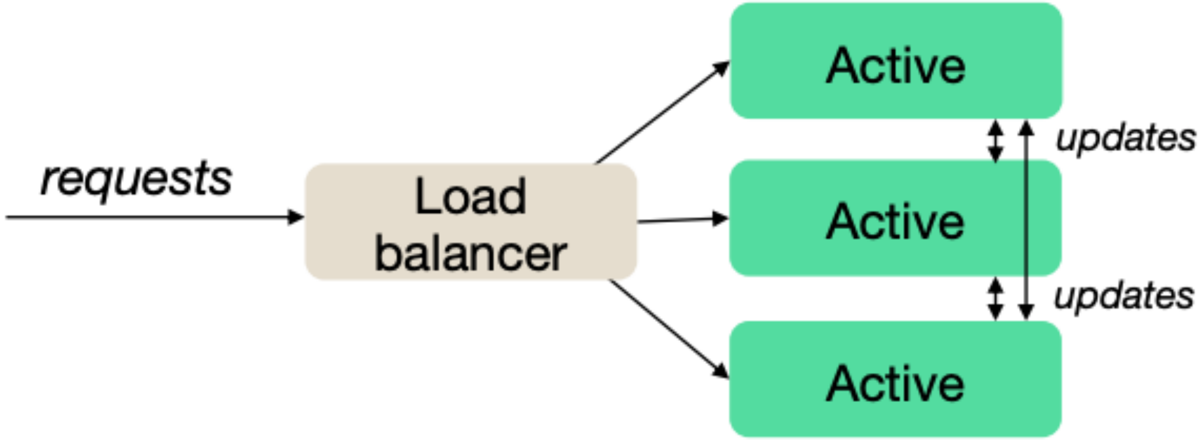




5. AVAILABILITY

- System Components Fail
  - Computers, processes, disks, memory, data centers etc
  - Replicas can take over
- Fault tolerance
  - Identify & recover from component failures
- Recoverability
  - Software can restart and function – May involve restoring state





6. 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
  - Failure transparency Lower-level software works around any failures – **things just work**

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DISTRIBUTED SYSTEM CHALLENGES

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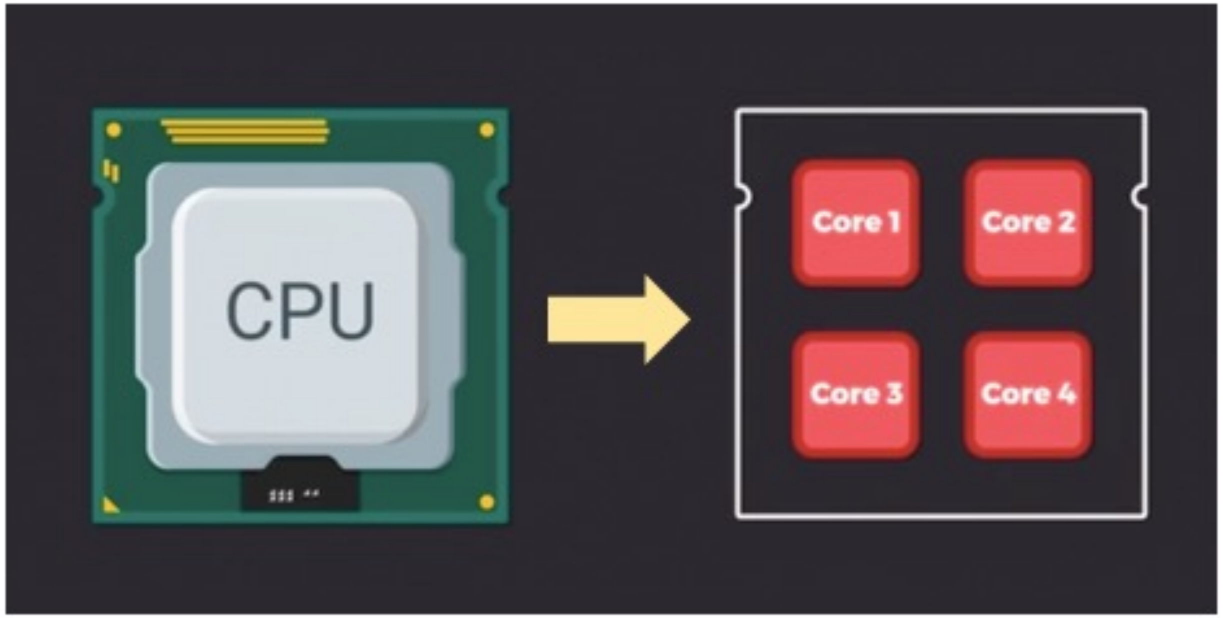
DISTRIBUTED SYSTEM CHALLENGES

1. Concurrency
2. Latency
3. Partial Failure
4. Security

DISTRIBUTED SYSTEM CHALLENGES

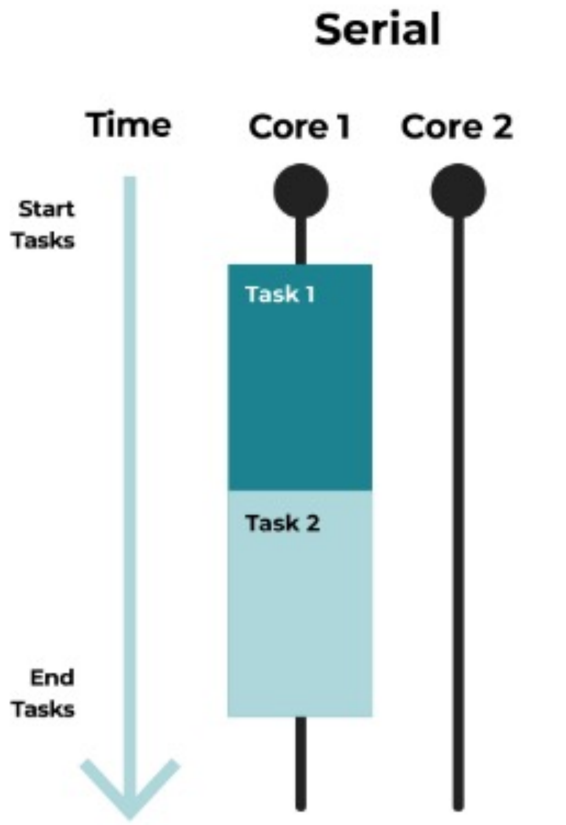
1. Concurrency
   - Modern processors have multiple cores
   - Each core can execute parts of a program
   - Lots of requests may occur at the same time
   - Need to deal with concurrent requests



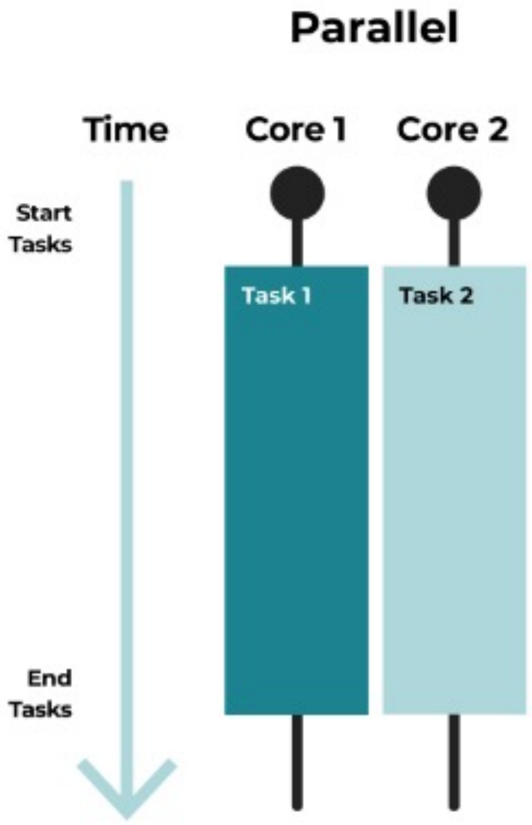
DISTRIBUTED SYSTEM CHALLENGES

1. Concurrency

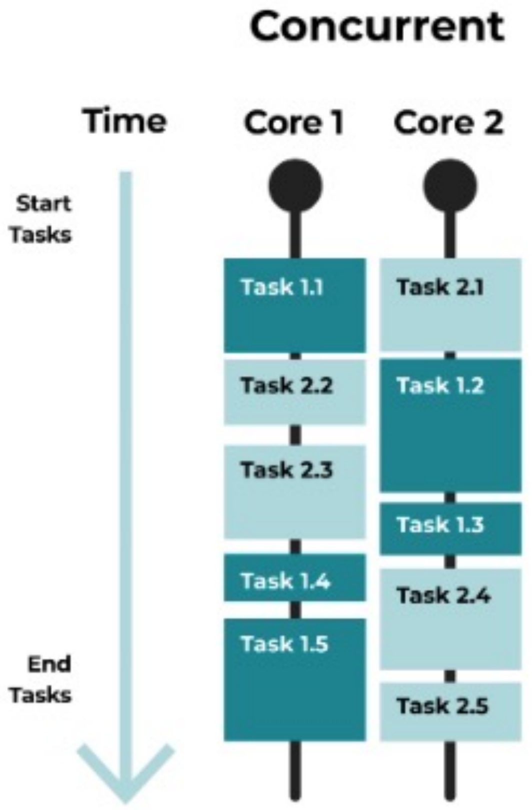
- Need to ensure consistency of all data



Serial execution of two tasks



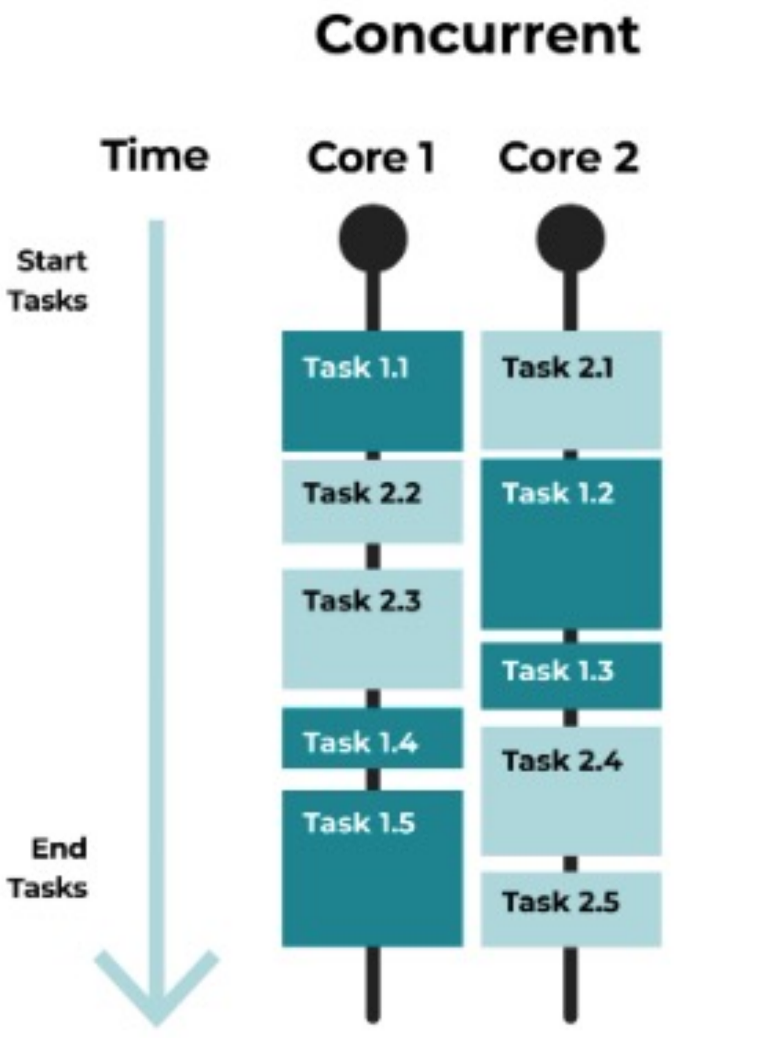
The parallel execution of two tasks



Two cores concurrently executing many tasks

DISTRIBUTED SYSTEM CHALLENGES

1. Concurrency
    - Understand **critical sections** & **mutual exclusion**
        - Beware: mutual exclusion (locking) can **affect performance**
    - Caching and replication costs
        - Complex; synchronization, message-delivery, check-sums etc



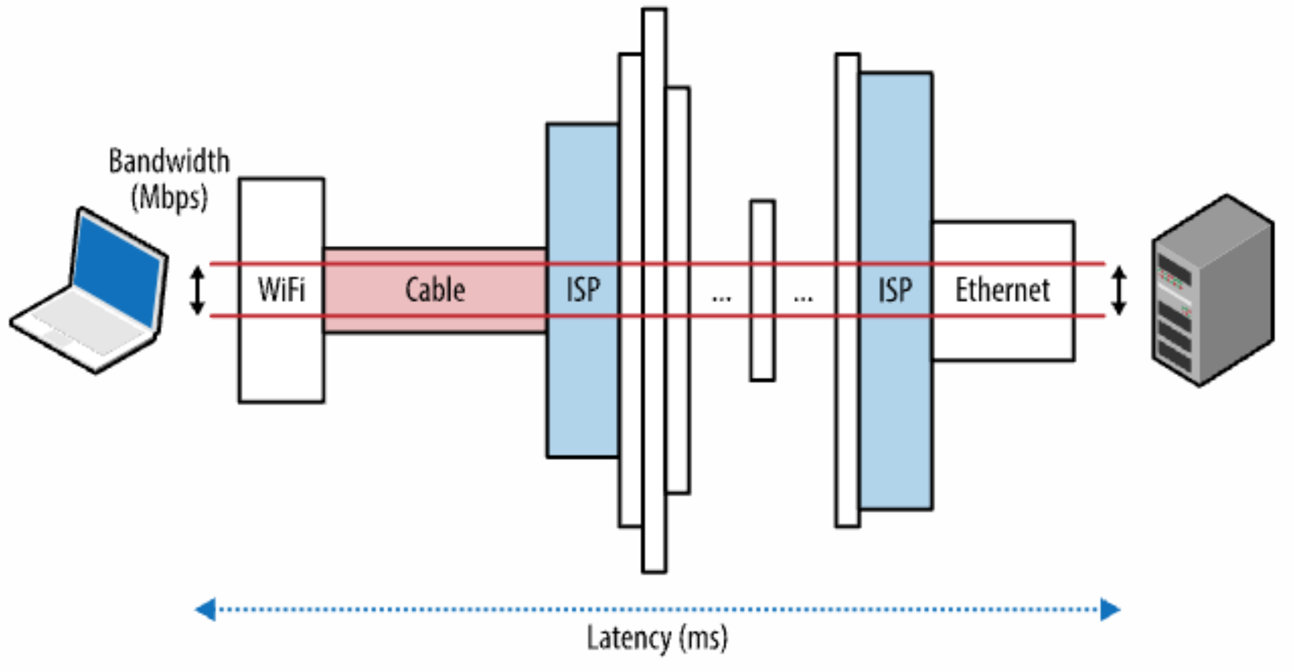
Two cores concurrently executing many tasks

DISTRIBUTED SYSTEM CHALLENGES

2. Latency

Communication {Time taken for a data packet to travel from the source to the destination across a network}

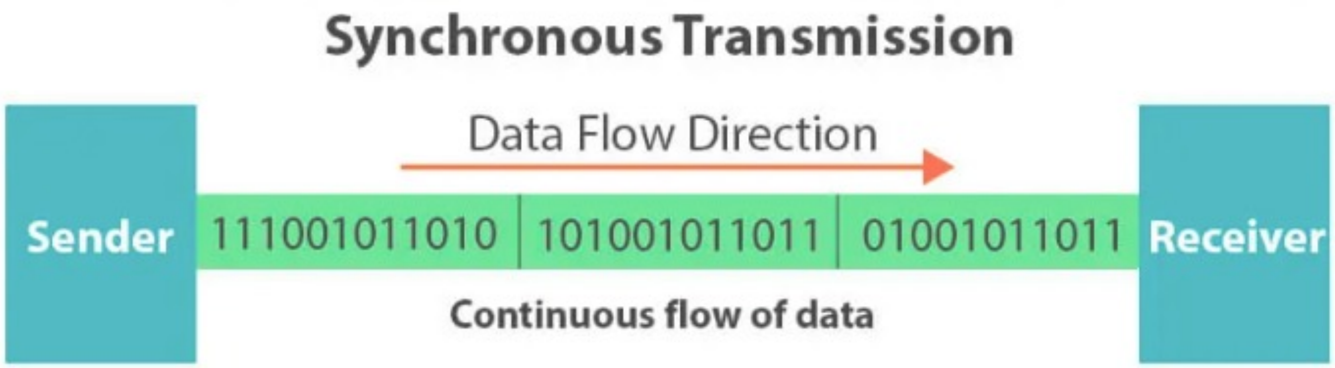
- **Propagation Delay**: The time it takes for a signal to travel through the medium
- **Transmission Delay**: The time required to push all the packet's bits into the wire.
- **Processing Delay**: The time taken by routers and switches to process the packet headers, check for errors, and route them appropriately.
- **Queuing Delay** … vitches due to congestion



DISTRIBUTED SYSTEM CHALLENGES

2. Latency

- Synchronous Communication Protocols
  - Both sender and receiver share a common clock signal, ensuring that data is transmitted and received at precise intervals.
  - Advantages: High throughput; Low overhead; Reduced latency
  - Disadvantages: Complex; Distance Limits; Cost
  - Examples: USB (Universal Serial Bus); Ethernet (at the Data Link Layer); I²C (Inter-Integrated Circuit):



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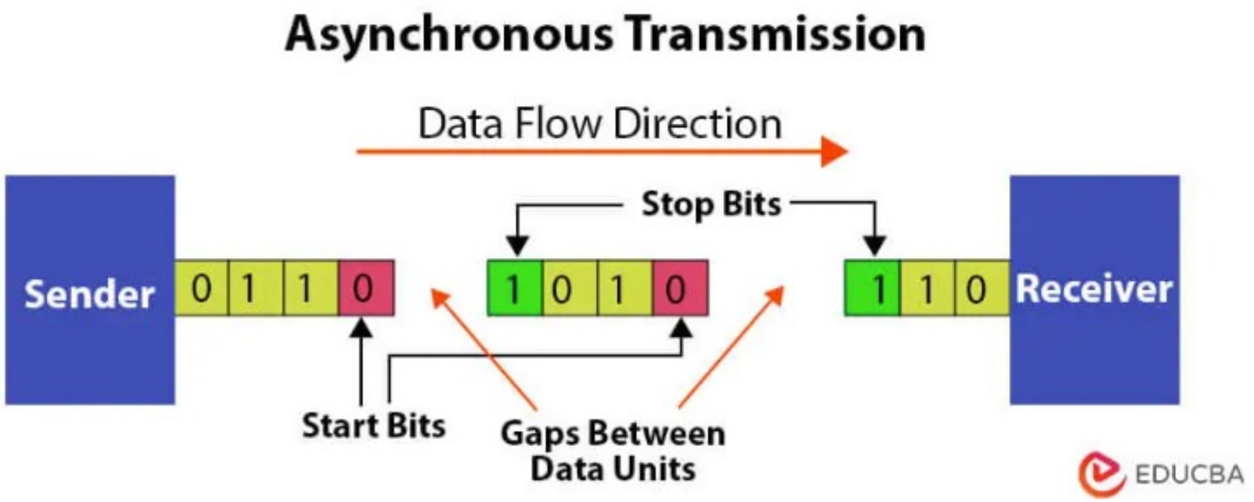
DISTRIBUTED SYSTEM CHALLENGES

2. Latency

- Asynchronous Communication Protocols
  - Sender and receiver DO NOT share a common clock signal. Communication can occur at any time.
  - Advantages: Flexible; Simple; Scalable
  - Disadvantages: Poor efficiency; High latency; Error handling



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DISTRIBUTED SYSTEM CHALLENGES

2. Latency

Storage {Read/Write speeds of the storage media}

- Traditional Storage: HDD – Most common and slow due to mechanical parts. (5-10 ms)
- SSD / NVme: Non volatile Electronics Memories (<20 micro seconds)
- RAM: Extremely low latencies (nano seconds)
- Cloud: High latency due to network delays

- **Caching**: Keep data close to where it's processed to maximize efficiency
  - Memory vs. disk
  - Local disk vs. remote server
  - Remote memory vs. remote disk

DISTRIBUTED SYSTEM CHALLENGES

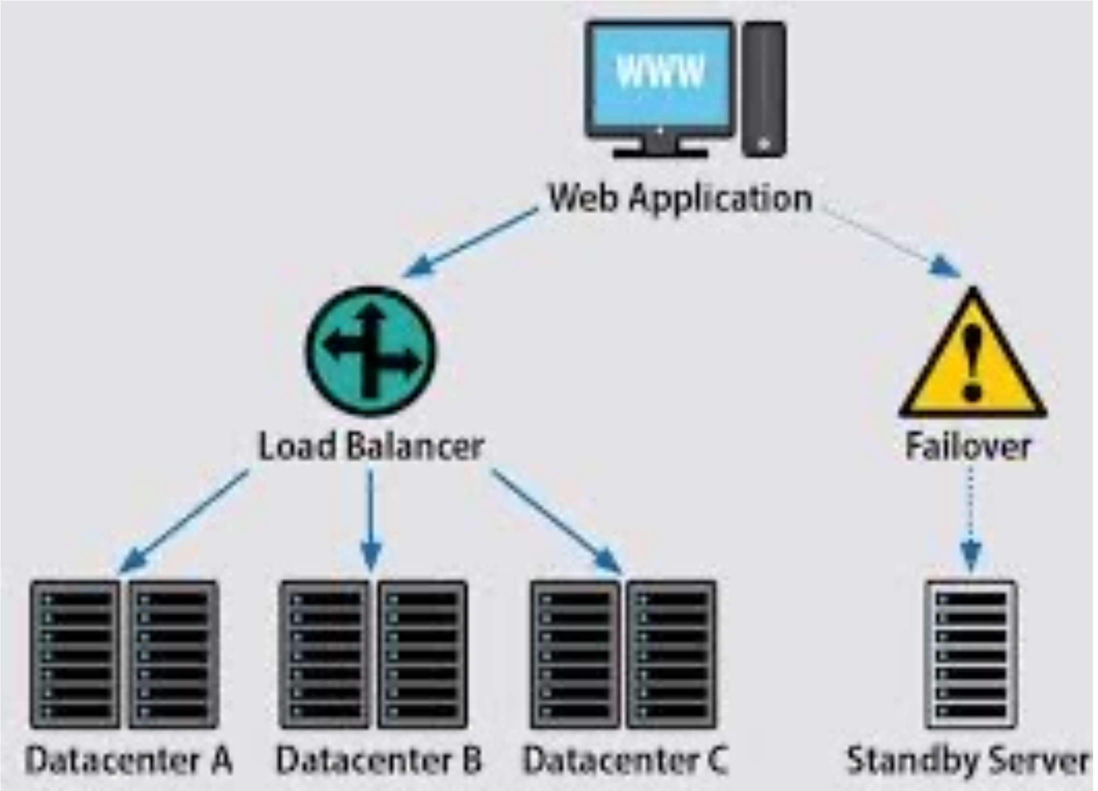
3. Partial Failure

- In local systems, failure is usually total (all-or-nothing)
- In distributed systems, we get partial failure
  - A component can fail while others continue to work
  - Failure of a network link is indistinguishable from a remote server failure
  - Sent a request but don't get a response ⇒ what happened?

DISTRIBUTED SYSTEM CHALLENGES

3. Partial Failure

- No global state
  - There is no global state that can be examined to determine errors
  - There is no agent that can determine which components failed and inform everyone else
- Need to ensure the state of the entire system is consistent after a failure



DISTRIBUTED SYSTEM CHALLENGES

4. Security

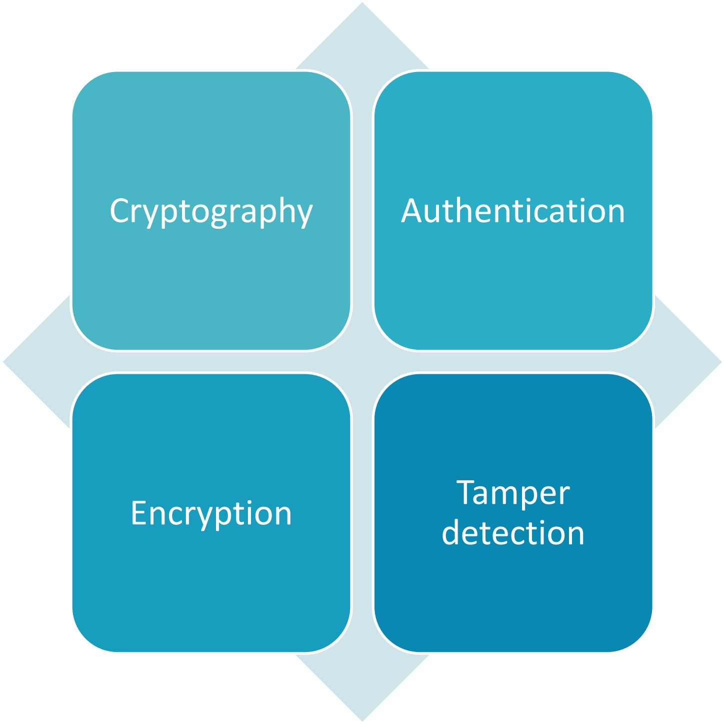
- Traditionally managed by operating systems
  - Users authenticate themselves to the system
  - Each user has a unique user ID (UID)
  - Access permissions = f(UID)
- Now applications must take responsibility for
  - Identification,
  - Authentication,
  - Access control,
  - Encryption,
  - Tamper detection,
  - Audit trail

Identification	Authentication
Access control	Encryption
Tamper detection	Audit trail

DISTRIBUTED SYSTEM CHALLENGES

4. Security

- The environment
  - Public networks, remotely-managed services, 3rd party services
  - Trust: do you trust how the 3rd party services are written & managed?
- Some issues:
  - Malicious interference, bad user input, impersonation of users & services
  - Protocol attacks, input validation attacks, time-based attacks, replay attacks
- Rely on cryptography (hashes, cryptography) for identity management, authentication, encryption, tamper detection … and also rely on good defensive programming!



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DISTRIBUTED SYSTEMS ARCHITECTURE

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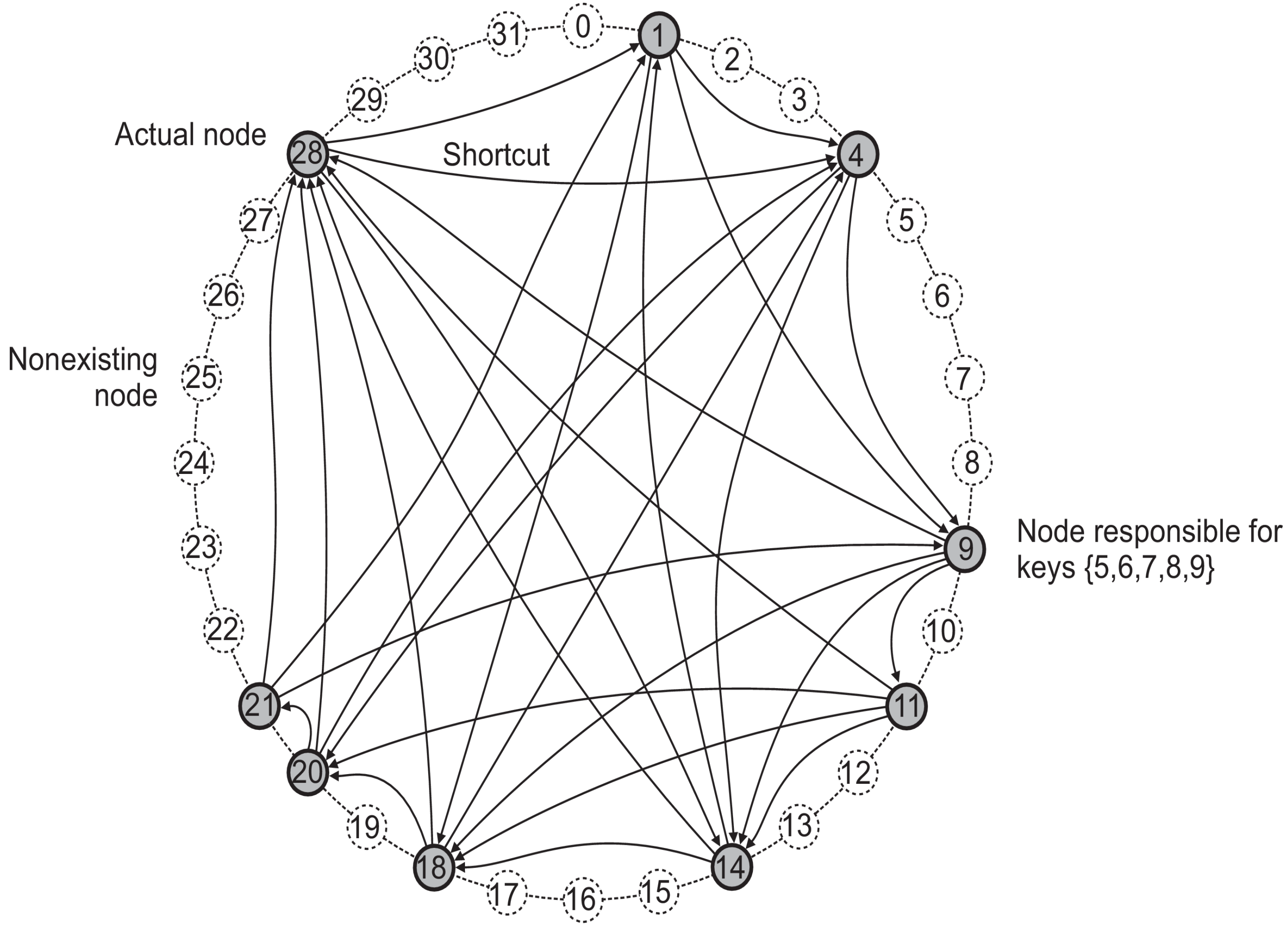
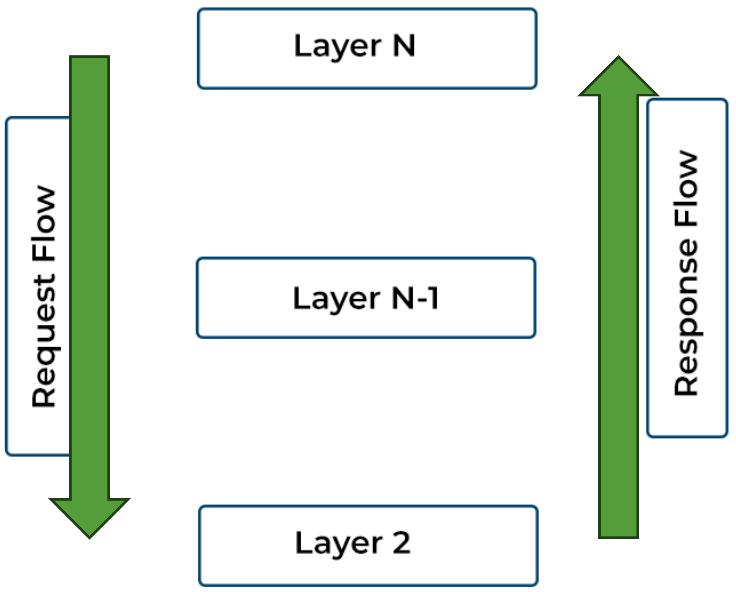
ARCHITECTURE

- Layered architecture
- Object architecture
- Data-centric architecture
- Event-based architecture
- Middleware
  - Centralized
  - Peer to Peer
  - Hybrid



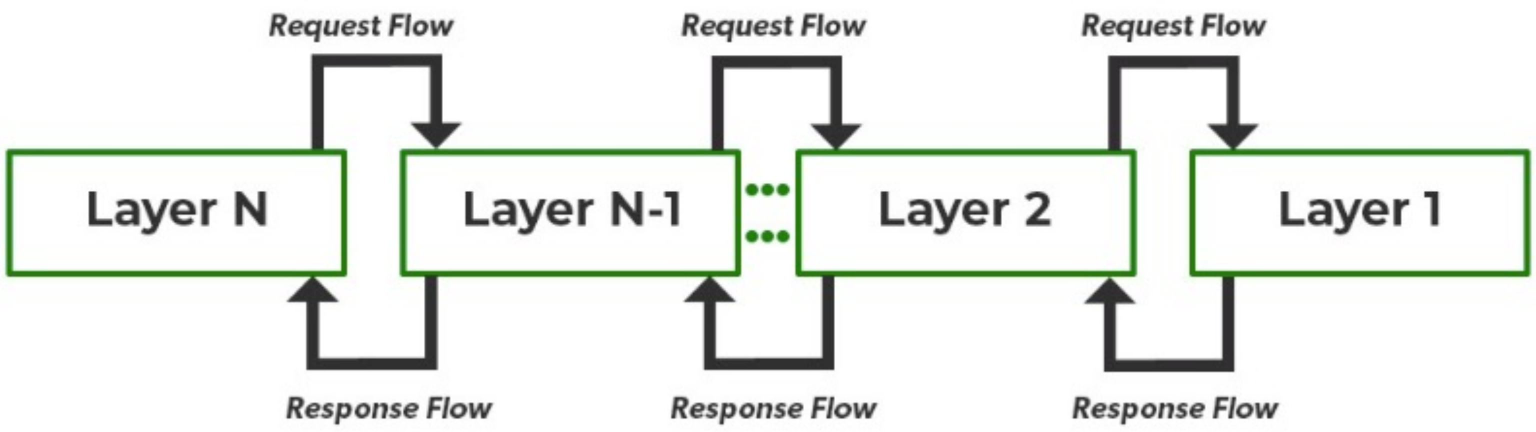
ARCHITECTURE

- Layered architecture
  - Components organized as layers
  - Information flows through layers.
  - Any layer can not directly communicate with another layer
  - No intermediate layer can be skipped!



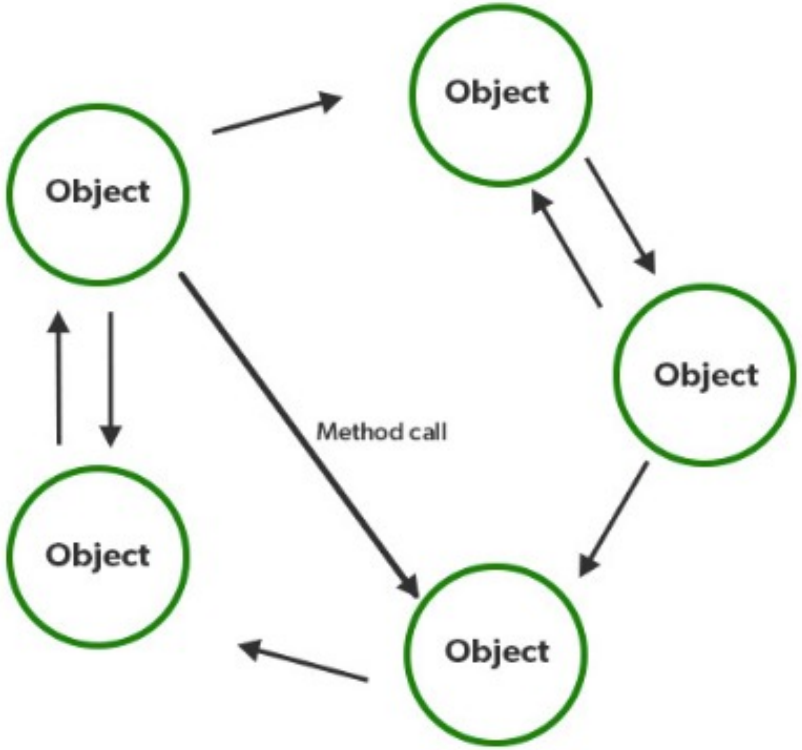
ARCHITECTURE

- Layered architecture
  - Advantage:
    - 1. Each layer can be modified independently without affecting the whole system.
    - 2. Calls always follow a predetermined path and that each layer is simple to replace or modify without affecting the architecture as a whole.
  - Examples: Network Open System Interconnection (OSI) model.



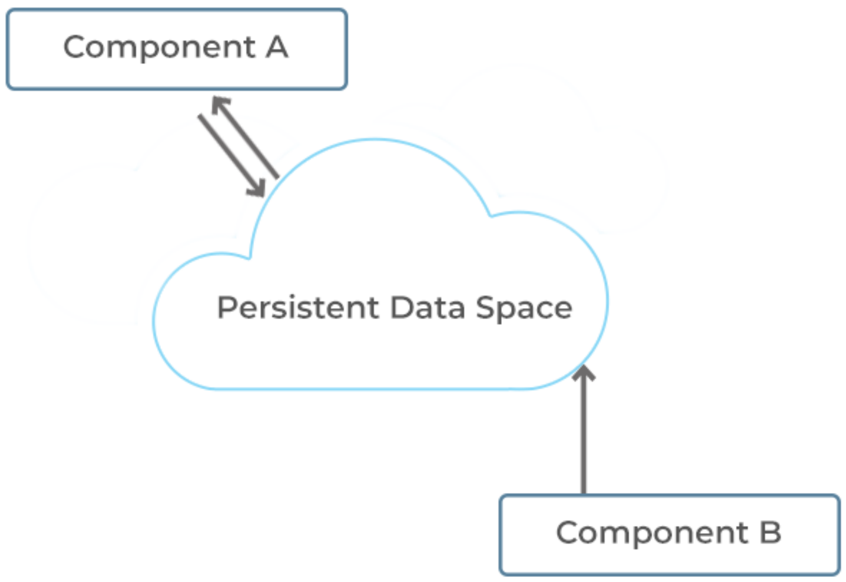
ARCHITECTURE

- Object based architecture
  - Contains an arrangement of loosely coupled objects.
  - Objects can interact with each other through method calls
    - e.g. Remote Procedure Call (RPC) mechanism or Remote Method Invocation (RMI) mechanism.
  - Examples: REST API Calls, Web Services, Java RMI



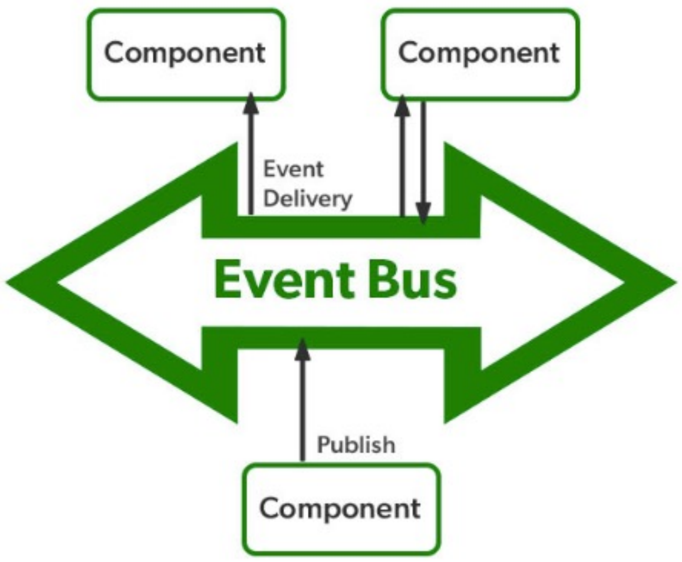
ARCHITECTURE

- Data centric architecture
  - Works on a central data repository, either actively or passively
  - All the components are connected to this data repository.
  - Producer-consumer communication model:
    - Producer produces items to the common data repository
    - Consumer (individual) can request data from the common data repository
  - Example: Web-based E-commerce systems



ARCHITECTURE

- Event based architecture
  - Events are present at the center in the Event bus and delivered to the required component as needed
    - When an event occurs, the system, as well as the receiver, get notified. Data, URLs etc are transmitted through events.
    - Components are loosely coupled. i.e., it's easy to add, remove, and modify components.
  - Example: Enterprise services buses; akka.io

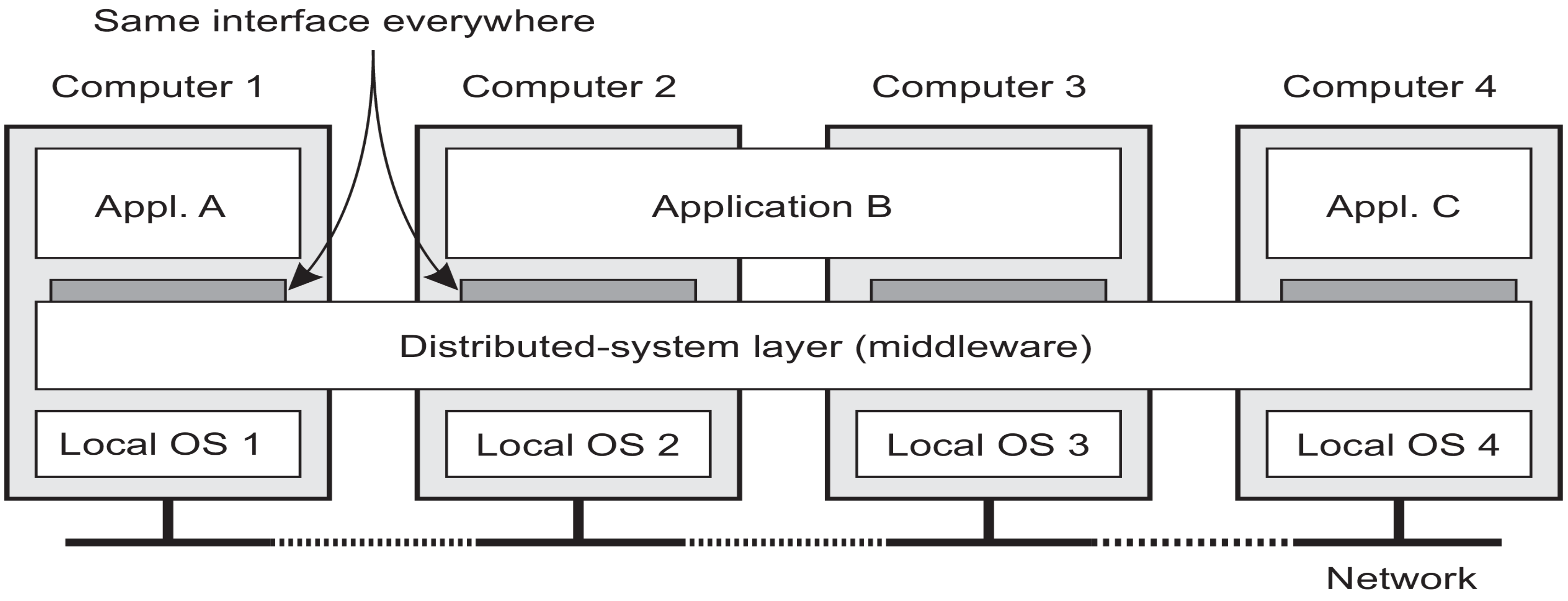


ARCHITECTURE

- Middleware: The OS of Dist Systems

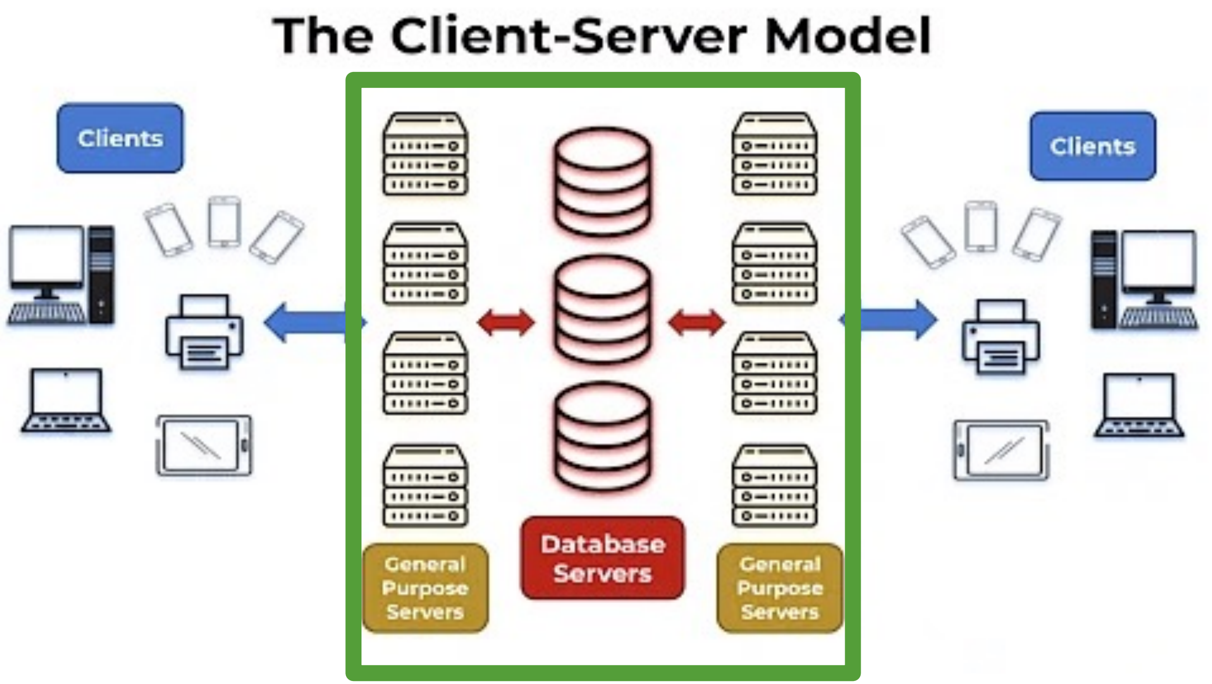
“The placement of components of a distributed system across multiple machines”

- Three possible architecture models
  - Centralized: Client-Server
  - De-centralized: Peer-to-Peer
  - Hybrid



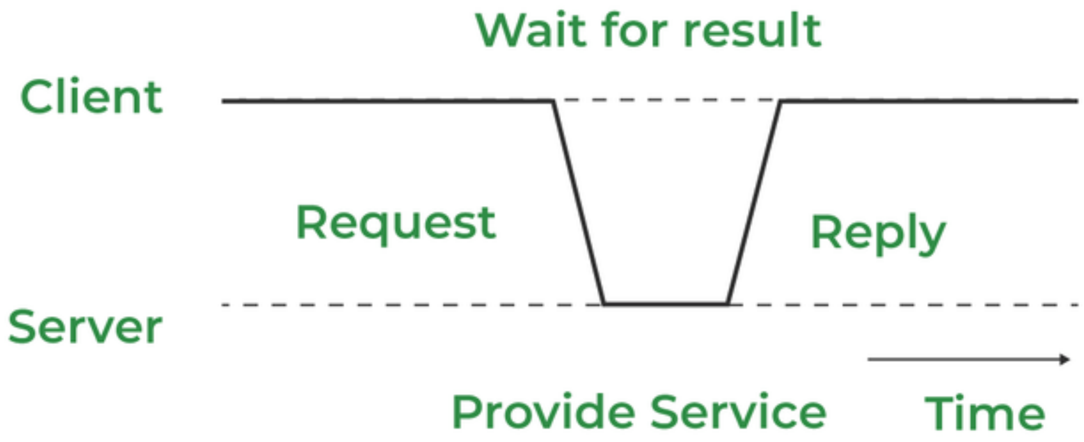
ARCHITECTURE: CLIENT-SERVER MODEL

- Centralized / Client-Server model
- Every node is connected to a central coordination system
  - **Client** – This is the first process that issues a request to the second process i.e. the server.
  - **Server** – This is the second process that receives the request, carries it out, and sends a reply to the client.



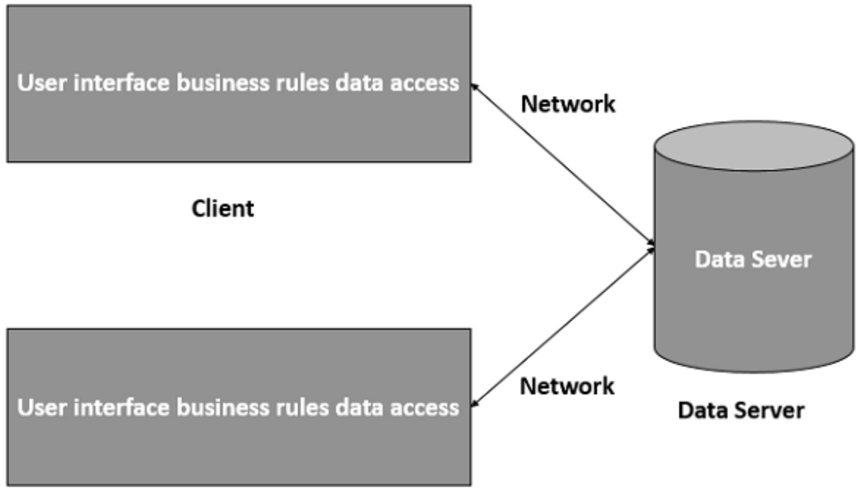
ARCHITECTURE: CLIENT-SERVER MODEL

- Client-server interaction/request-reply behavior.
  - Server: a process that implements a service (exp: file system service, database service).
  - Client: a process that requests a service from a server
- Communication between a client and a server can be:
  - Connectionless protocol [if reliable connection available].
  - Connection oriented protocol [otherwise, e.g. TCP/IP].



ARCHITECTURE: CLIENT-SERVER MODEL

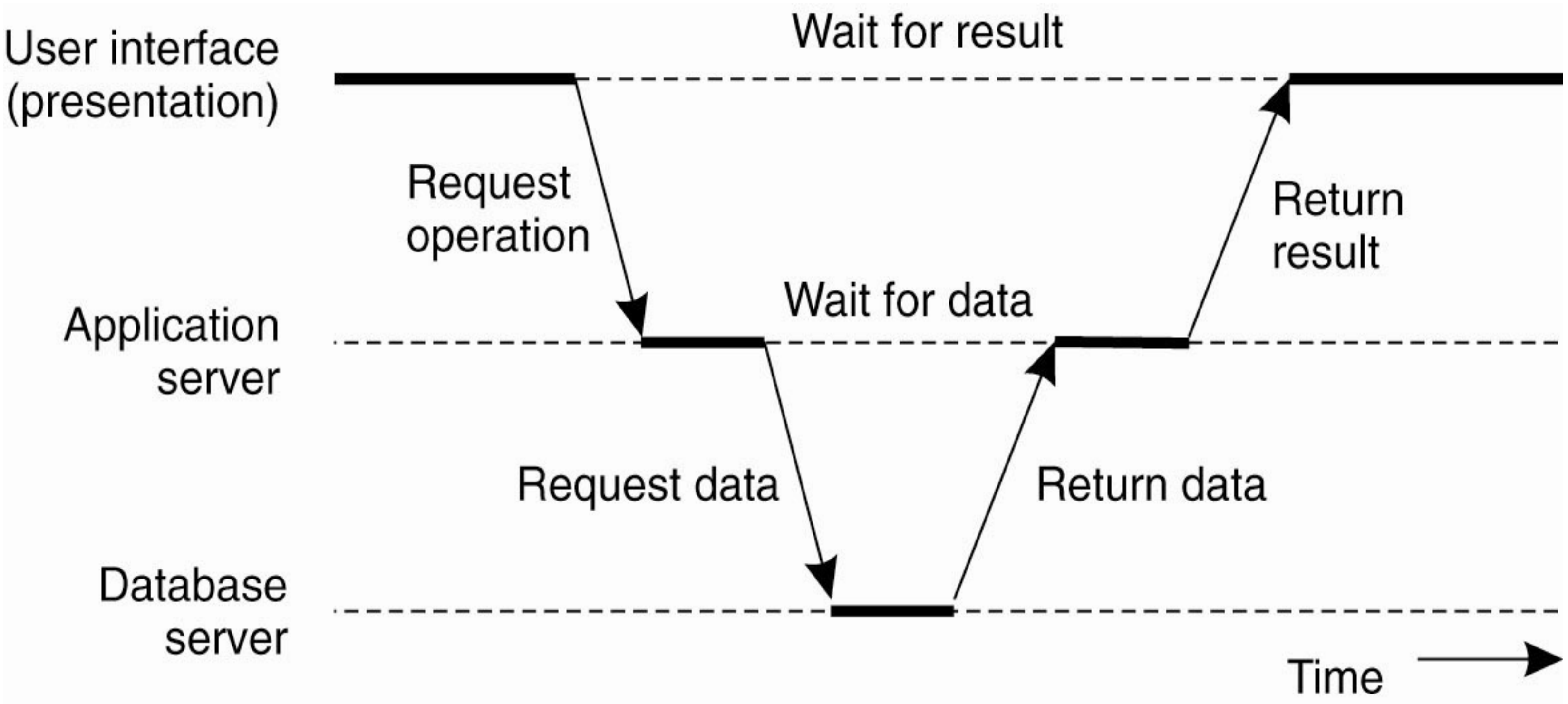
- 2-tier Client server architecture
  - The servers need not know about clients
  - The clients must know the identity of servers
  - Mapping of processors to processes is not necessarily 1 : 1
- Thin Client Model
  - Server: Application processing and data management
  - Client: Provide interface of the application
- Thick Client Model
  - Server: Data management only
  - Client: Complex data processing and interface



2 – Tier Client Server Architecture

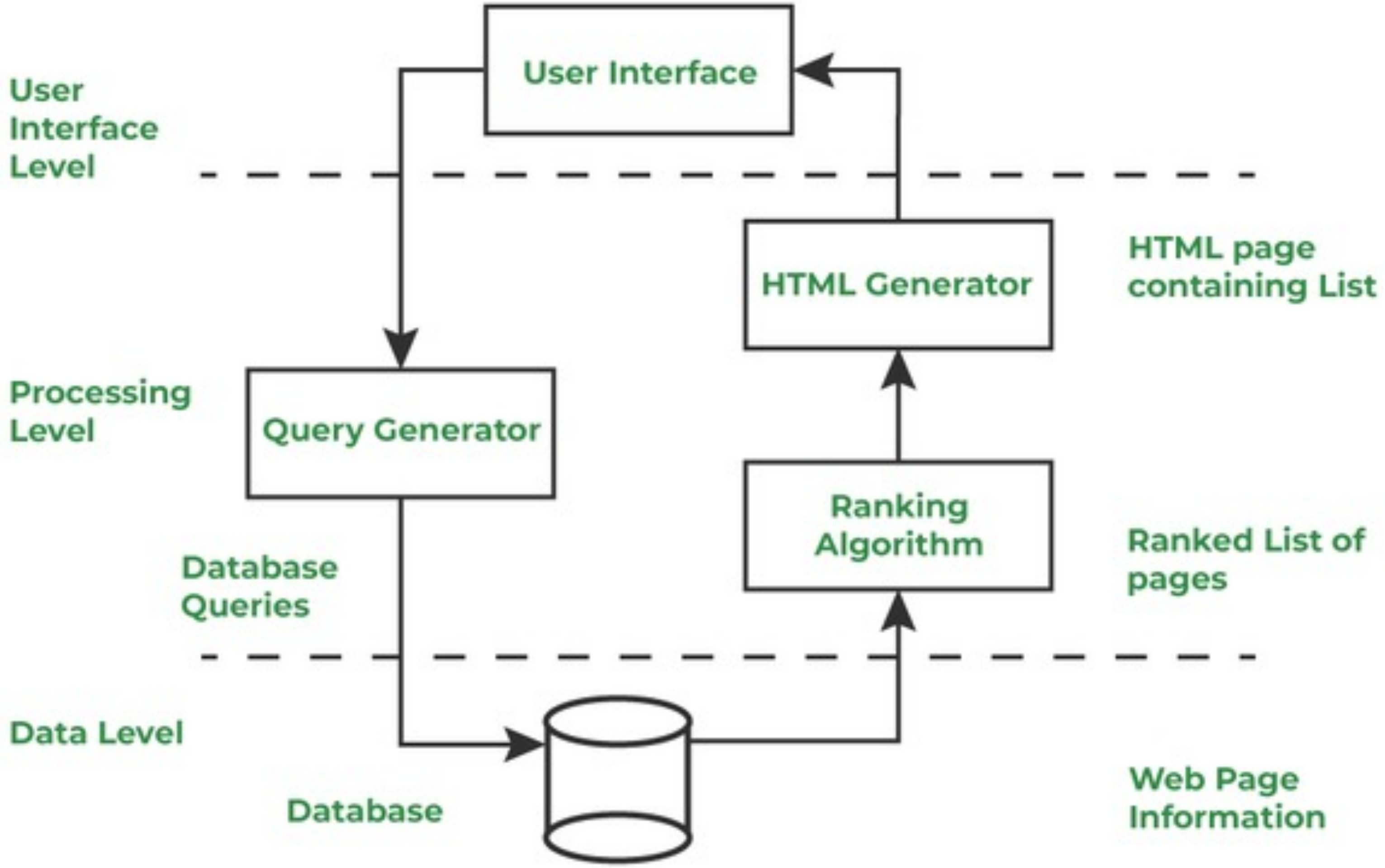
ARCHITECTURE: CLIENT-SERVER MODEL

- n-tier Client server architecture
  - Multi tier allows separate tier for a functionality of an application
  - 3-tier is common with Web/App-server, DB-server and Client-browser



ARCHITECTURE: CLIENT-SERVER MODEL

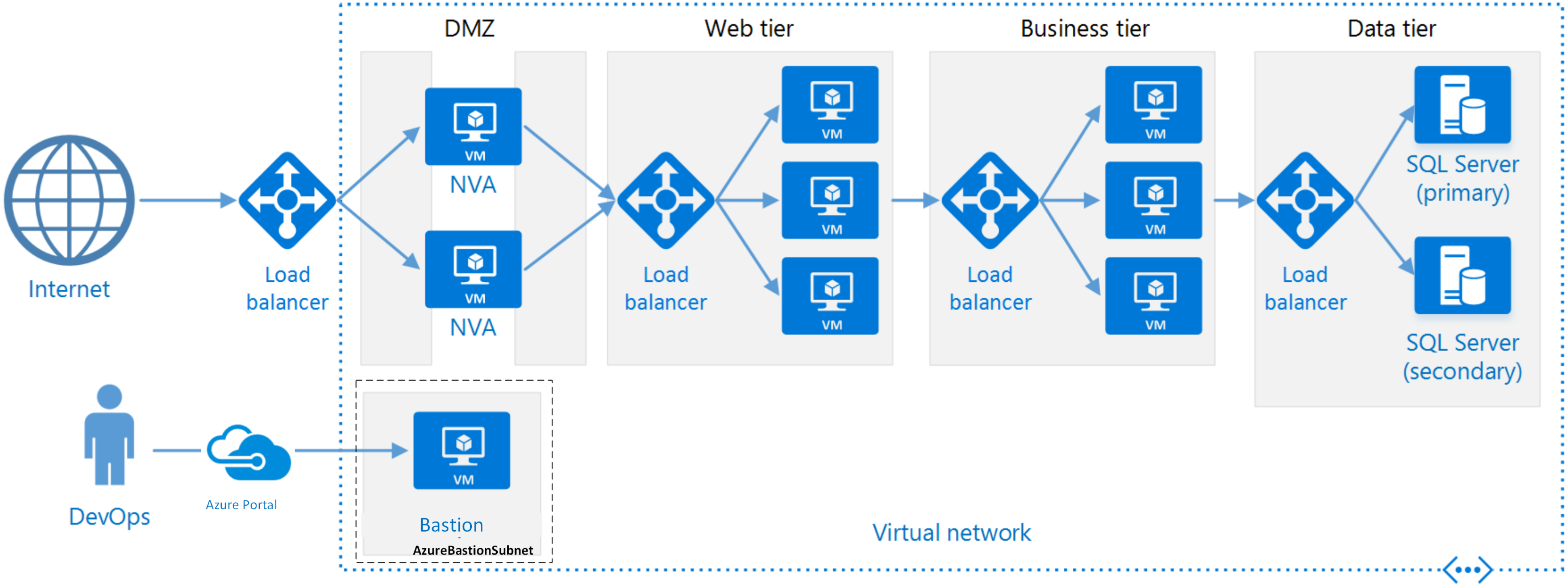
- 3-tier arch. example:
  - Internet Search Engine



Internet search engine into three different layers

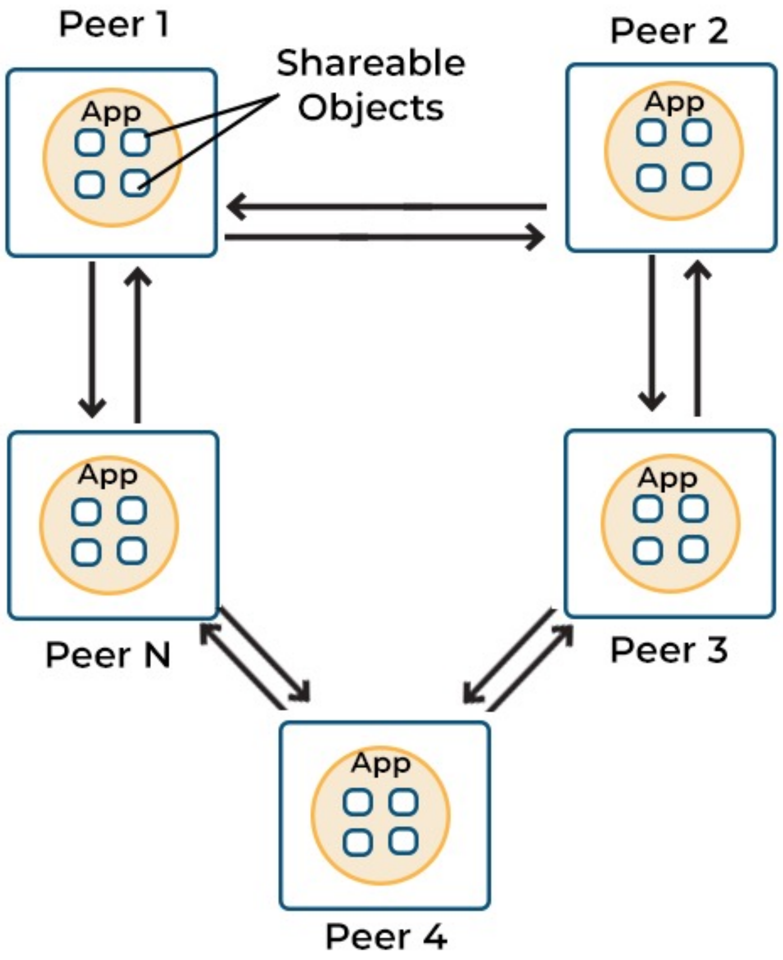
ARCHITECTURE: CLIENT-SERVER MODEL

- n-tier arch. example:
  - An MS Azure application using multiple Virtual Machines



ARCHITECTURE: P2P MODEL

- De-Centralized / Peer to Peer model
  - No central control
  - A node can either act as a client or server at any given time once it joins the network
  - Each node in the network has the same set of responsibilities and capabilities.



ARCHITECTURE: P2P MODEL

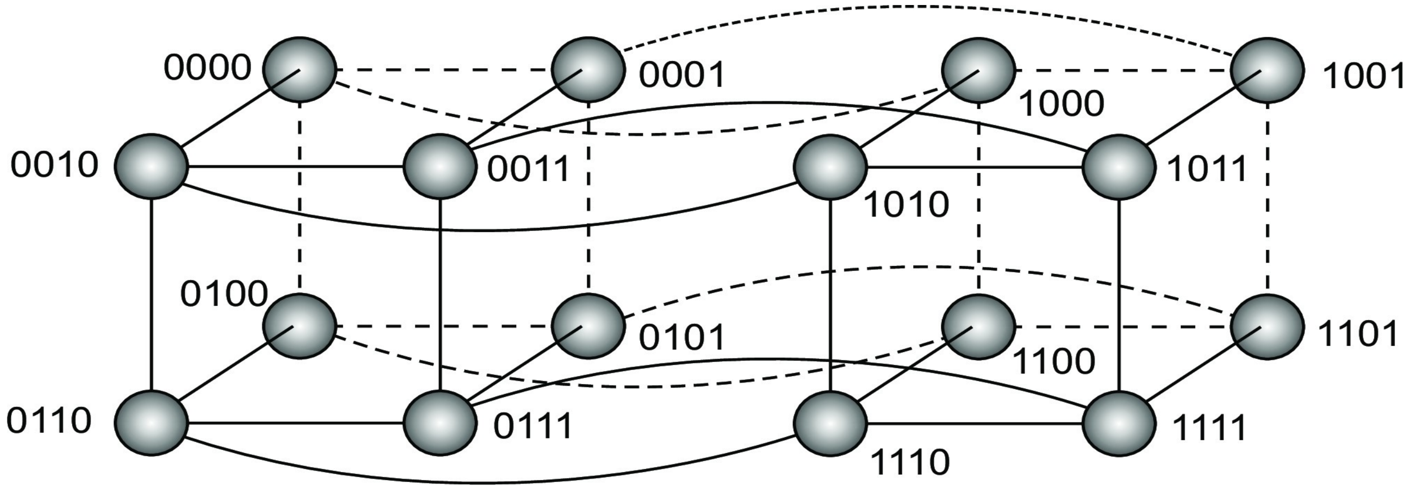
- Benefits:
  - Autonomy: Each node is independent of the other.
  - Less costly: No need to buy an expensive server.
  - No network manager
  - Adding nodes is easy: Adding, deleting, and repairing nodes in this network is easy.
  - Less network traffic than in a client/ server network.
- Challenges:
  - Less secure
  - Data is vulnerable. Stored in various nodes.
  - Slow performance

ARCHITECTURE: P2P MODEL

- Organization:
  - **Structured P2P**: Nodes adhere to a predefined distributed data structure.
  - **Unstructured P2P**: Networks feature nodes that randomly select their neighbors.
  - **Hybrid P2P**: Systems combine elements of both, with certain nodes assigned unique, organized functions.

ARCHITECTURE: P2P MODEL

- Structured P2P:
  - Typically maintains a **Distributed Hash Table (DHT)**
  - Each peer is responsible for a specific part of the content in the network.
  - Network use hash functions and assign values to every content and every peer.
  - A global protocol determines which peer is responsible for which content.
  - Whenever a peer wants to search for data, it uses the global protocol to determine the peers responsible for the data and then directs the search towards the responsible peers.

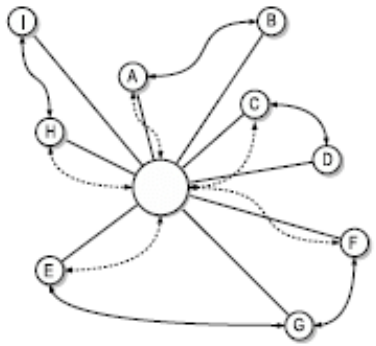


ARCHITECTURE: P2P MODEL

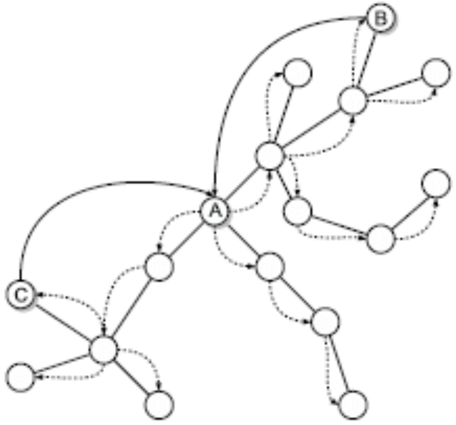
- Un-structured P2P:
  - Lack a predefined organization or topology for how nodes are connected.
  - Do not rely on distributed hash table (DHT).
  - More flexible and dynamic.
  - They are often used for applications where the focus is on simplicity, ease of deployment, and adaptability.

Challenges:

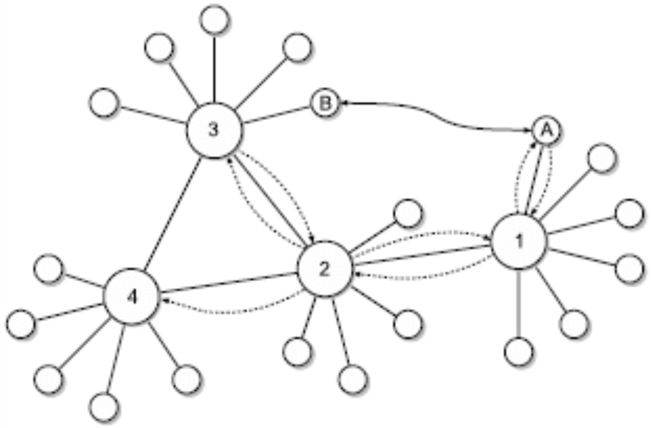
- Scalability issues
- Increased search
- Efficiency
- Reliability.



(a) Napster & BitTorrent



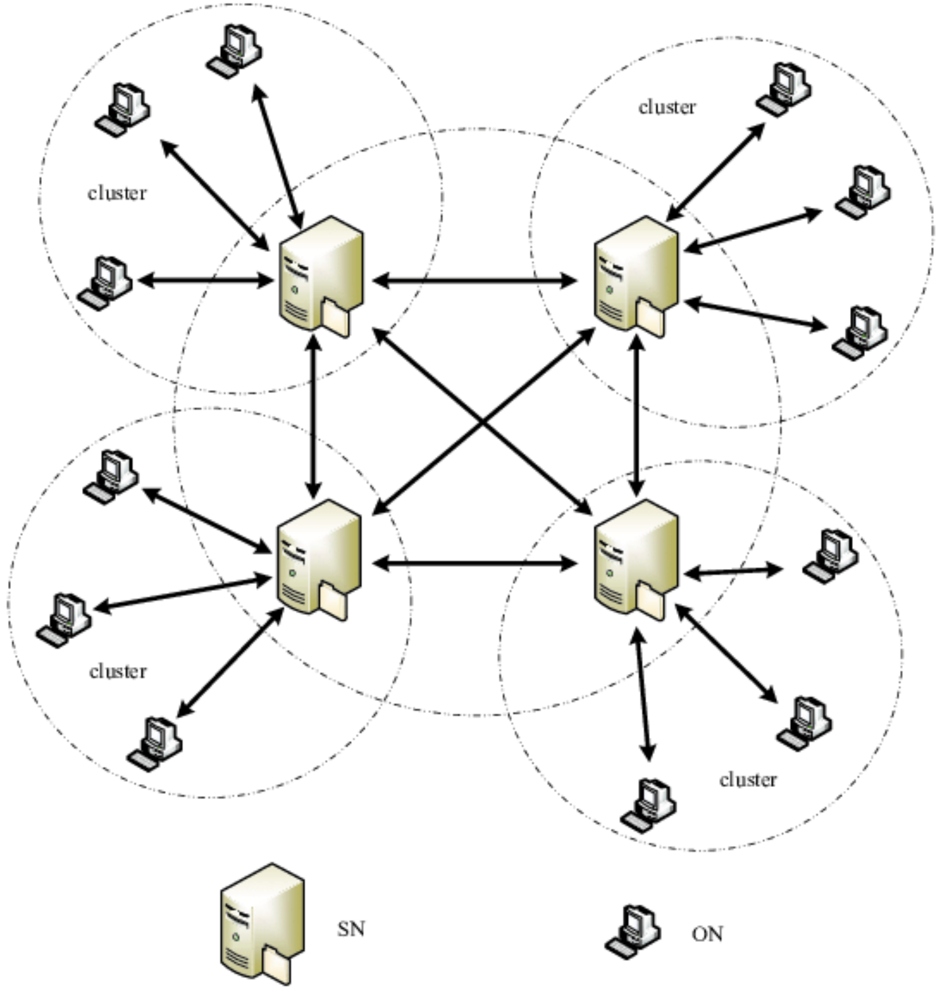
(b) Gnutella



(c) Gnutella/Overnet/eDonkey2000

SYSTEM ARCHITECTURE: HYBRID MODEL

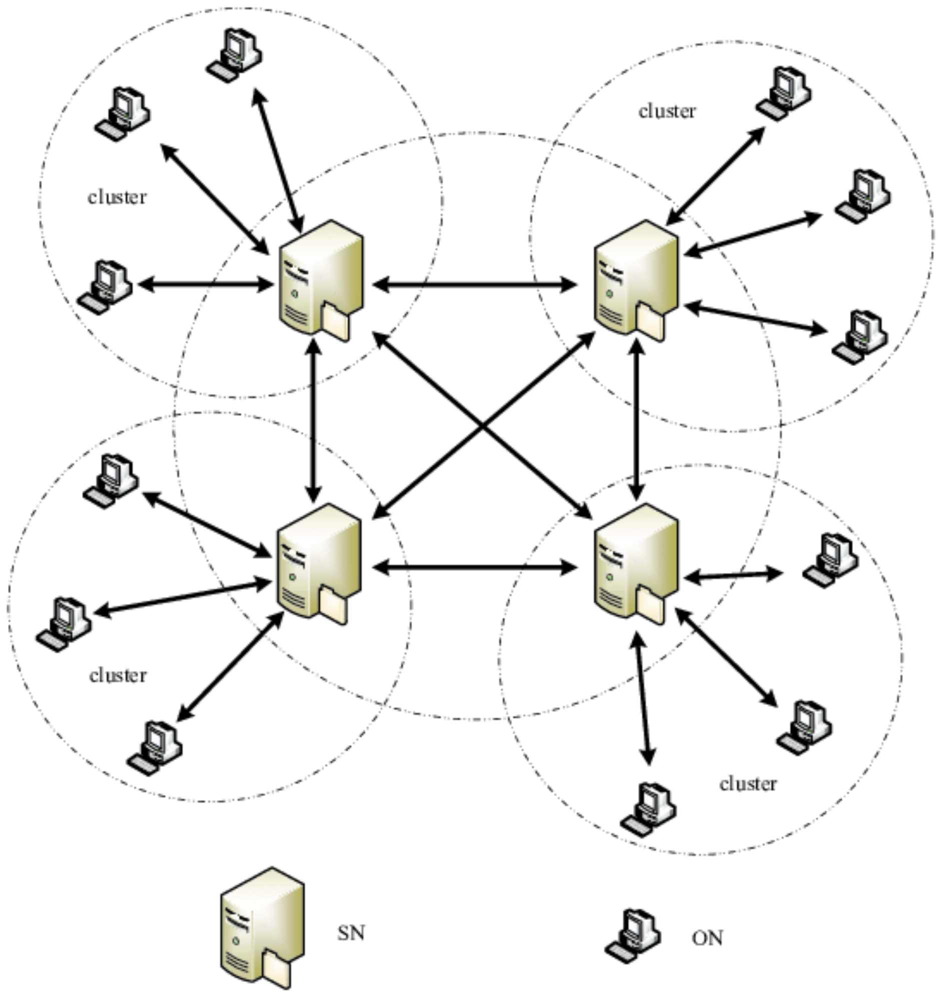
- Hybrid P2P/Client Server:
  - A combination of peer-to-peer and client–server models.
  - A common hybrid model is to have a central server that helps peers find each other
  - There are a variety of hybrid models, all of which make trade-offs between the centralized functionality and pure peer-to-peer unstructured networks.
  - Currently, hybrid models have better performance than either pure unstructured networks or pure structured networks.



Shunzhi Wang, Zhanyou Ma, Rong Wang et al. Performance analysis of a queueing system based on working vacation with repairable fault in the P2P network, 21 September 2022, Supercomputing [https://doi.org/10.21203/rs.3.rs-1864515/v2]

SYSTEM ARCHITECTURE: HYBRID MODEL

- Benefits
  - Efficient Data Retrieval
  - Scalability
  - Adaptability and Flexibility
  - Fault Tolerance
  - Load Balancing
  - Dynamic Resource Discovery
- Challenges
  - Complexity
  - Overhead
  - Consistency
  - Increased Latency
  - Resource Utilization
  - Security and Privacy Concerns



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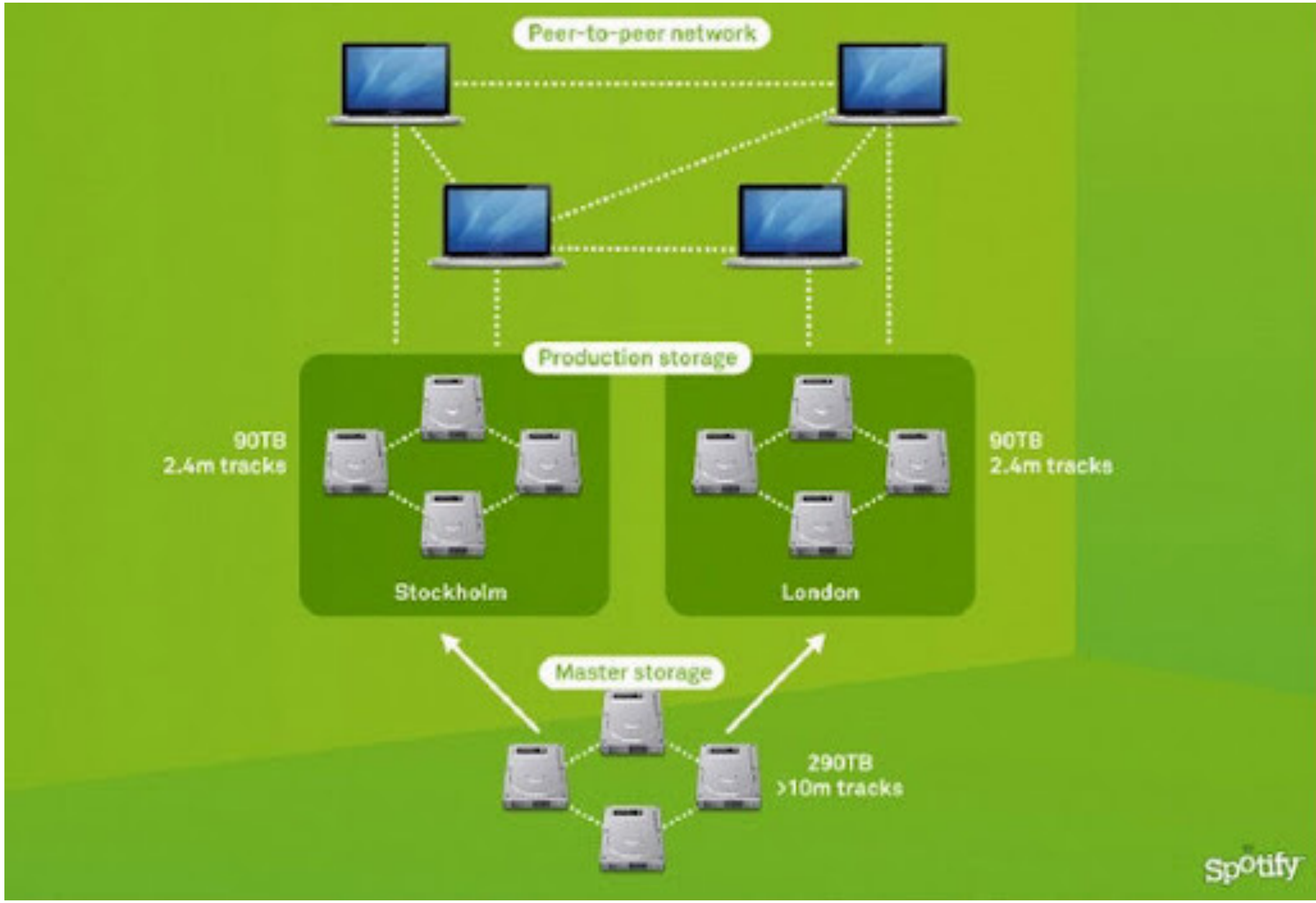
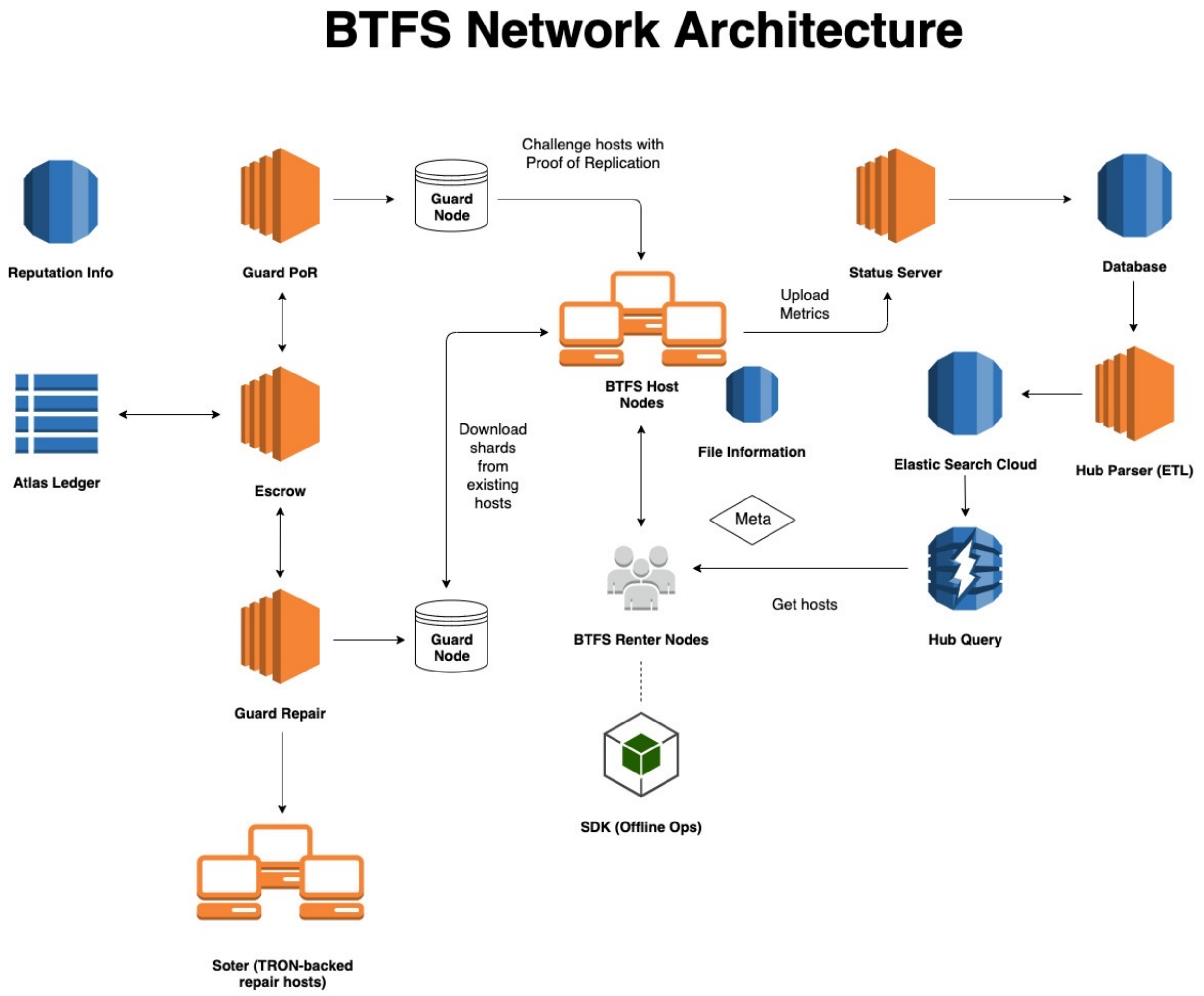
SYSTEM ARCHITECTURE: HYBRID MODEL

- Hybrid P2P-Client-Srvr:
  - Example: Spotify (before 2014)



SYSTEM ARCHITECTURE: HYBRID MODEL

- Hybrid P2P-Client-Srvr:
  - Example: Bittorent



https://docs.btfs.io/v1.0/docs/what-is-btfs#architecture

SYSTEM ARCHITECTURE: HYBRID MODEL

- Hybrid P2P-Client-Srvr:
  - Example: Deep Torrent crawler

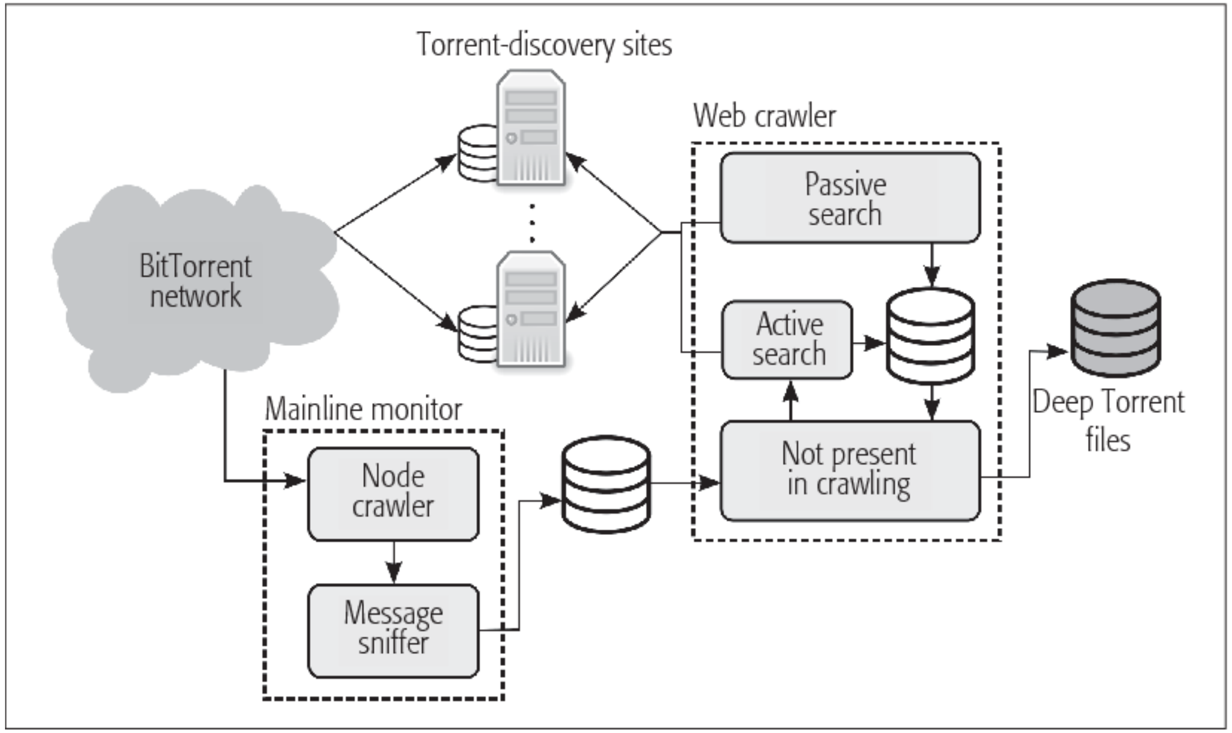
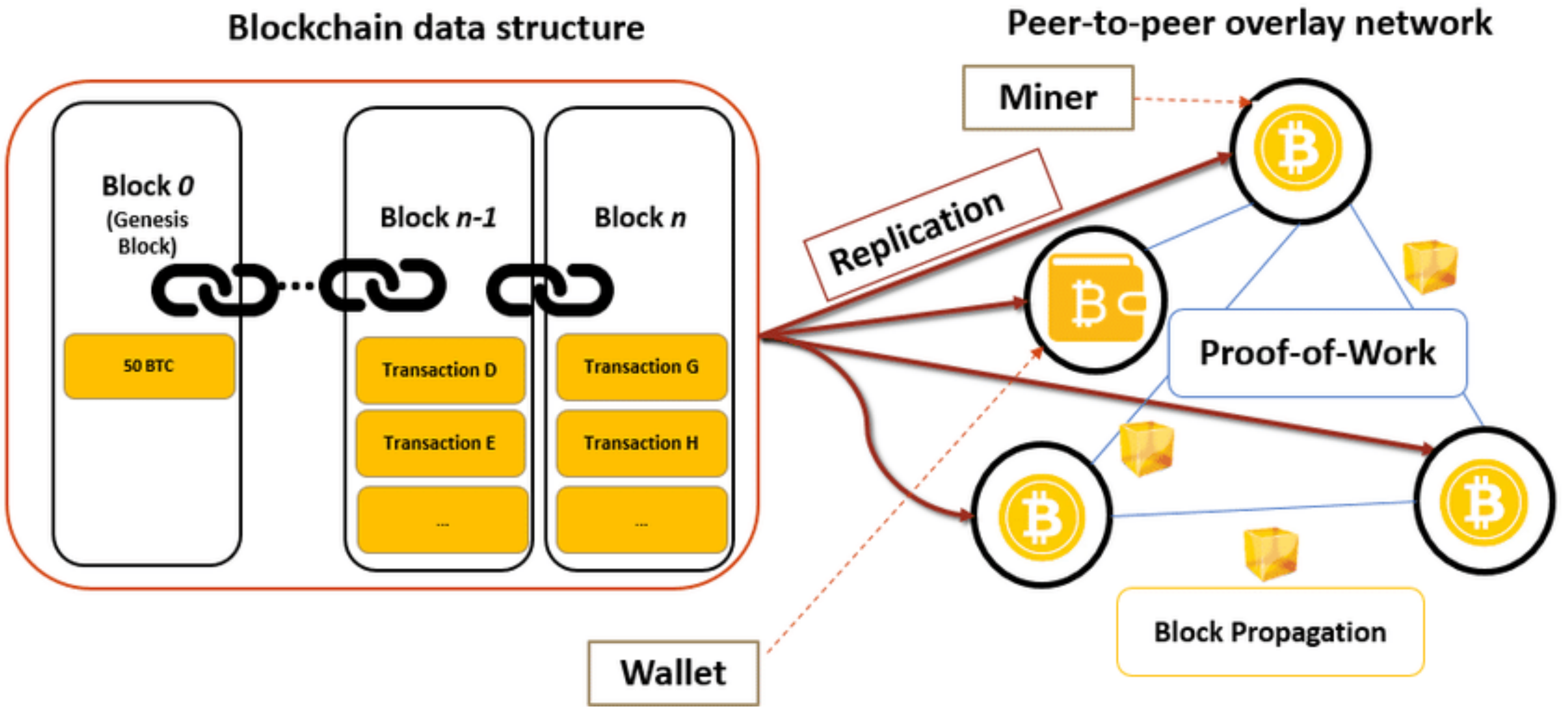


Figure 1. Functional architecture of the Deep Torrent crawler.

Rodríguez-Gómez, Rafael et al. "On Understanding the Existence of a Deep Torrent." *IEEE Communications Magazine* 55 (2017): 64-69.

SYSTEM ARCHITECTURE: HYBRID MODEL

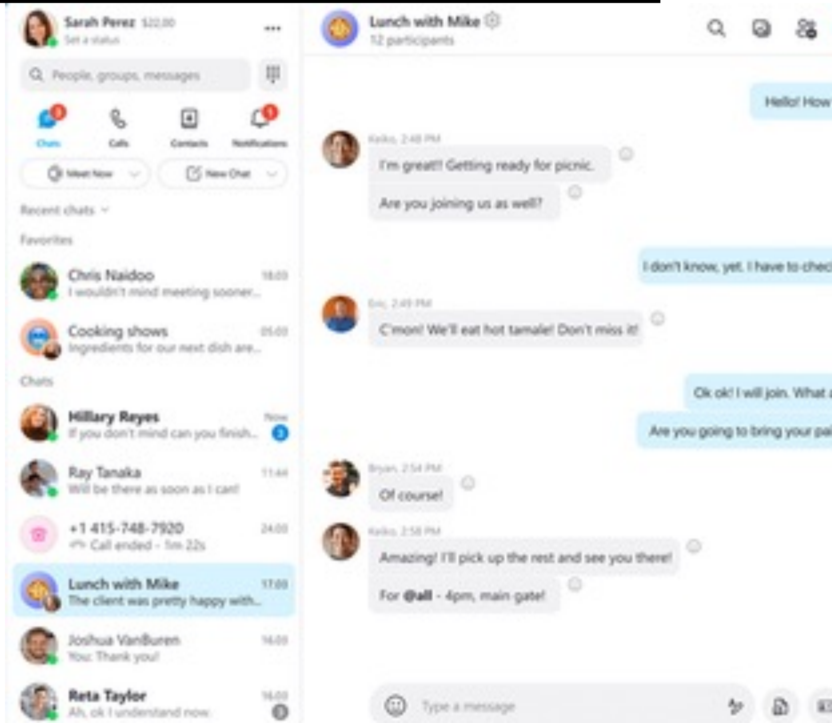
- Hybrid P2P-Client-Srvr:
  - Example: Bitcoin, Etherium Blockchain



Y. Shahsavari, K. Zhang and C. Talhi, "Performance Modeling and Analysis of the Bitcoin Inventory Protocol," *2019 IEEE International Conference on Decentralized Applications and Infrastructures (DAPPCON)*, Newark, CA, USA, 2019, pp. 79-88, doi: 10.1109/DAPPCON.2019.00019.

SYSTEM ARCHITECTURE: HYBRID MODEL

- Hybrid P2P-Client-Srvr:
  - Other Examples: Gnutella, eDonkey, Kazaa, Napster, Skype etc



CS435 Distributed systems

DISTRIBUTED SYSTEMS SERVICES

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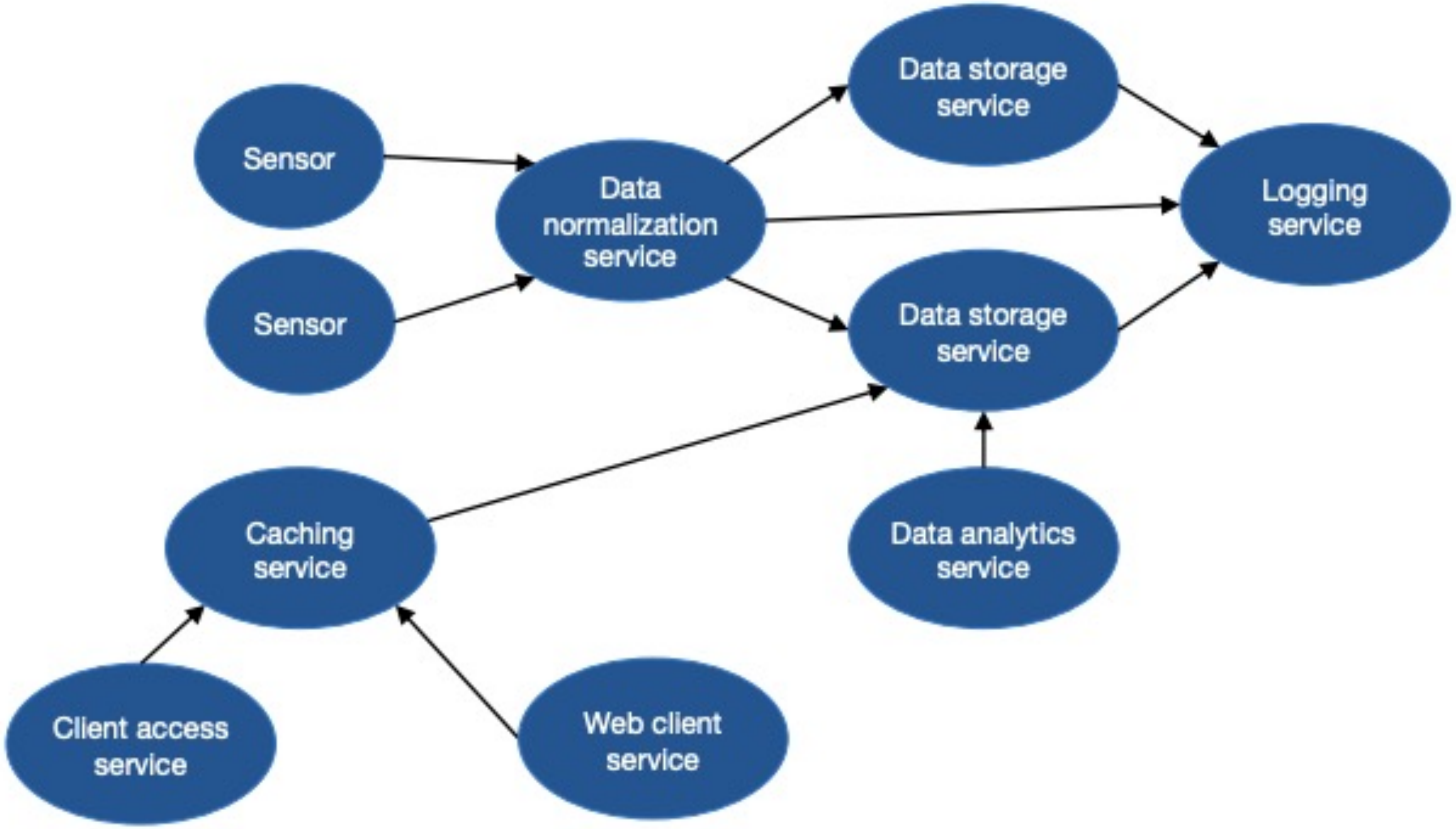
DISTRIBUTED SYSTEMS SERVICES

- A distributed system is a collection of services accessed via network interfaces



DISTRIBUTED SERVICES

- **Serverless Computing:** Developers focus on writing code without worrying about infrastructure management.
- **Edge Computing:** Bringing computing resources closer to the data source, enabling faster processing and reduced latency.
- **Container Orchestration:** Simplifying the deployment and management of distributed services using container orchestration platforms.

DISTRIBUTED SERVICES

- Serverless Computing:
  - Depends on underlying physical servers, however there is no server hardware or operating system environment to manage for developers or IT engineers.
  - Abstracts applications from the underlying server and operating system, serverless functions are easier to deploy and manage
  - Event-driven computing; use resources as you go; deploy serverless functions and APIs
  - More efficient than conventional applications that run constantly
  - Auto-scaling enabled, cost-effective

DISTRIBUTED SERVICES

- Edge Computing:
  - Moves some portion of storage and compute resources out of the central data center and closer to the source of the data itself.
  - Compute, Store, Network, Service closer to the data-source.
  - Lighter, faster, efficient, cheaper.
  - Examples: Security system monitoring, IoT devices, Self-driving cars, Medical monitoring devices, Video conferencing etc.

DISTRIBUTED SERVICES

- Kubernetes and Container Orchestration
  - A container is a standard unit of software that packages up code and all its dependencies so the application runs quickly and reliably from one computing unit
  - Container orchestration automatically provisions, deploys, scales, and manages containerized applications without worrying about the underlying infrastructure.
  - Developers can implement container orchestration anywhere containers are, allowing them to automate the life cycle management of containers.

SUMMARY

- Distributed Systems Themes
- Dist. Sys. Challenges
- Dist. Sys. Architectures
- Distributed Services