An introduction to distributed systems

Runtimes for concurrency and distribution

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Distribution requires transparency

- A distributed system is a set of **independent** computing nodes capable of appearing as a **single** coherent execution platform to applications running on it
  - This requires all coordination communications among those computing nodes to be completely **transparent** to the application
- **Transparency** is given *when you get to see the intended effects without being exposed to the mechanics that produce them*
  - There exist several dimensions of transparency

What is transparency – 1

ISO/IEC 10746-1:1998, *Open Distributed Processing – Reference model: Overview*

Transparency of	To hide what
Access	Differences in data encoding or in the way operations happen on actual data
Location	Where computing resources actually reside (e.g., physical vs logical naming)
Migration / Relocation	Resources may move without the user needing to know in between uses, or even during use
Replication / Transaction	That a resource may exist in multiple coherent copies, or may result from the aggregation of multiple parts
Malfunction	Individual computing nodes may locally fail without this affecting the availability of the resource
Persistency	How writing succeeds regardless of the distance between writer and resource

What is transparency – 2

- In 1998 those traits of transparency sounded visionaries or far-fetched
- In 2021 we take them fully for granted …

Transparency requires openness

- A crucial prerequisite to **portability** and **interoperability**
- Openness prescribes all external interfaces to conform to **public** and **stable** specifications
- Such specs have to be
  - **Complete**, so that no details are hidden that may preclude third-party implementations of them
  - **Neutral**, so that they do not impose a single way of implementation
- Interface definition languages (IDL) help achieve such properties across language-specific views

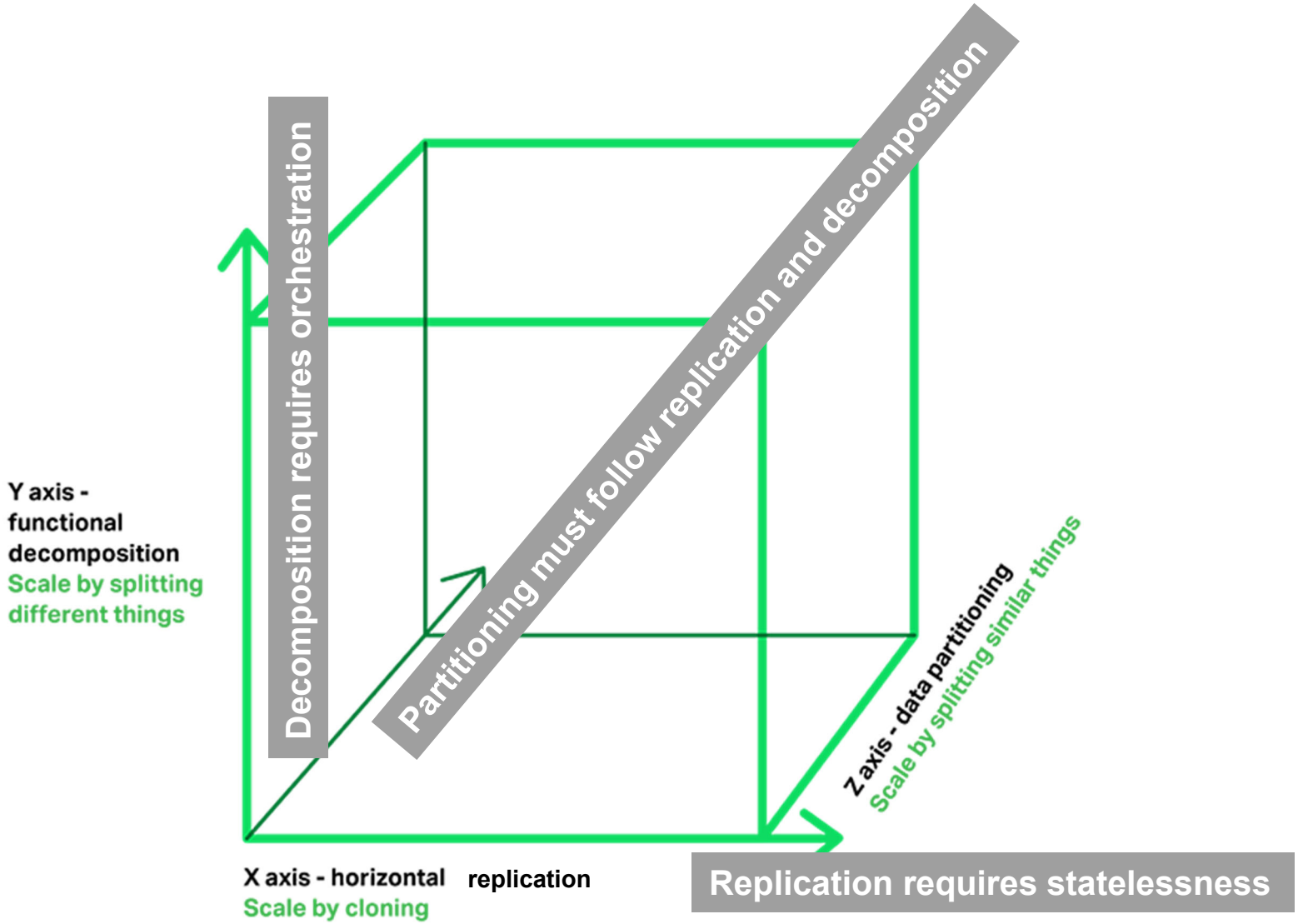
Distribution requires scalability

- Scalability is more easily understood by its negation
  - A system is **not** scalable when it is *unable* to accommodate increasing workload
    - The consequences of that may be failure at the client (`exit -1`) or at the server (e.g., buffer overflow, DoS, …)
- A useful definition stipulates scalability as
  - The ability to handle increased workload *by repeatedly applying a cost-effective strategy for extending system capacity*
    - Without intolerable latency or excessive waste

What is scalability

- *Fitness for purpose* with respect to
  - Availability of resources
    - They should never be scarce
  - Latency with respect to physical distance
    - The user should have perception of locality
  - Independence of global view from local issues
    - Issues in handling local, concrete implementation should not determine how a resource is presented to the user
- Where unused resources cost dearly, you want scalability to be **elastic**
  - Not only expanding but also contracting, with equal cost-effectiveness

The scale cube



https://www.nginx.com/blog/introduction-to-microservices/

The opposite of distribution

- Centralization of service
  - All users must refer to a single entry point
    - As in the `HOSTS.TXT` file that mapped hostnames to IP addresses in the ARPANET
- Centralization of resources
  - All the data relevant to a service are kept in a single copy at a single place
    - The opposite of how the DNS (ca. 1985) and Blockchain (ca. 2008) work
- Centralization of algorithm
  - Requiring to know the system state
    - Impossibly burdensome to compute and maintain

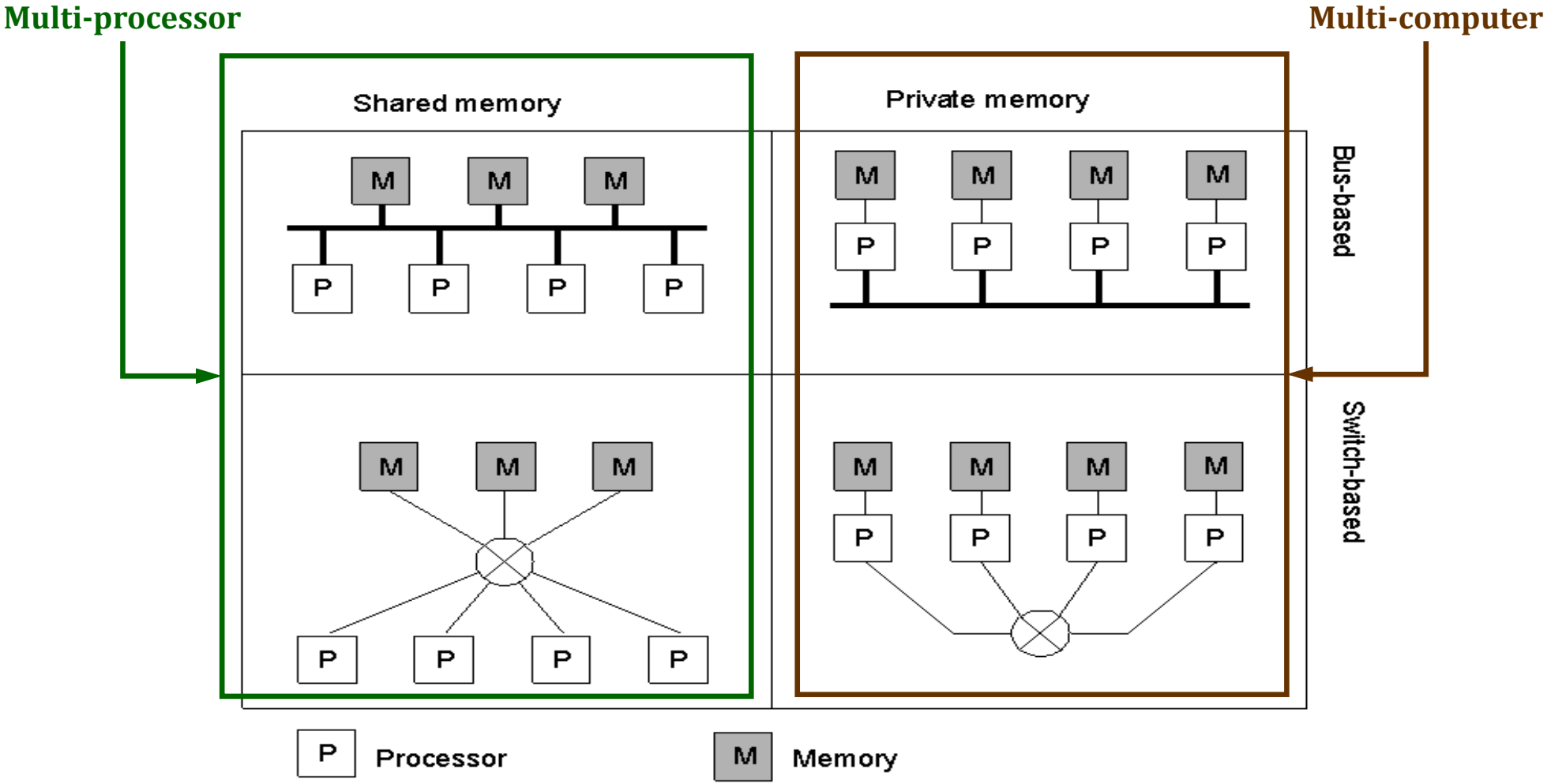
Prerequisites of distribution – 1

- An algorithm is distributed if
  - Every part of it acts satisfactorily on the basis of *local* knowledge
    - The DNS is partitioned
    - Blockchain is trustworthily replicated
  - Its computation does not require knowledge of global status
    - Local responses contribute to global result (DNS)
    - Local responses have global effect if confirmed by peers (Blockchain)
  - Local faults do not cause global failure
  - Its logic does not require a single source of time
  - It allows *consistent* replication of services, decomposition of tasks, partitioning of resources

Prerequisites of distribution – 2

- Synchronous communication *obstructs* distribution
  - It blocks the communicating parties delaying the progress of computation and causing coupling
- Asynchronous communication *enables* distribution
  - It decouples the communicating parties by hiding network delays, and allows independent progress

Hardware distribution

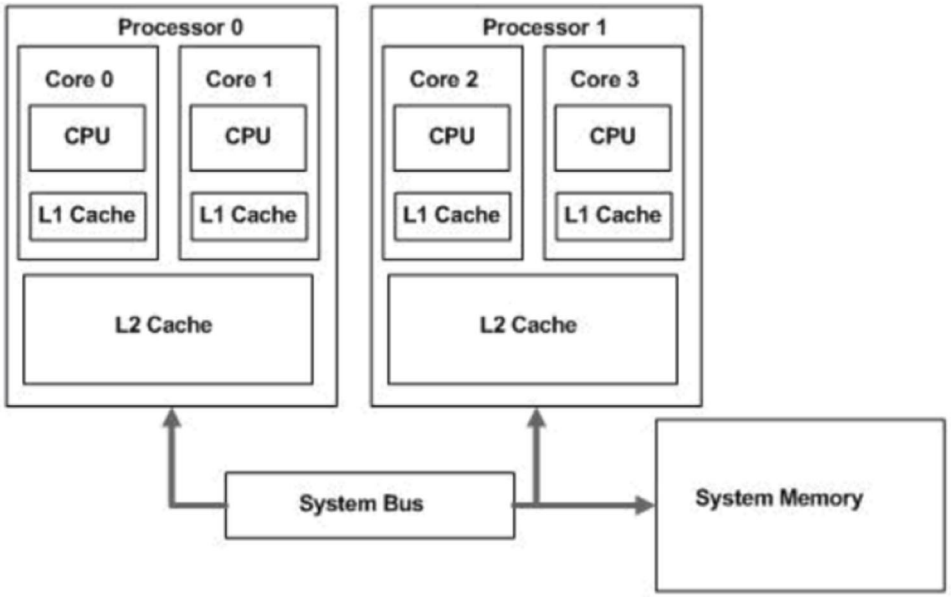


Distributed memory architecture

- Uniform memory access (UMA)
  - A *single* address space
    - As in symmetric multiprocessors
  - All node access memory in the same way
    - Access requests need queuing and arbitration
  - Cache coherence is not obvious
- Not-uniform memory access (NUMA)
  - Address space is shared but not unified
  - Access to memory depends on location
  - Cache coherence is unthinkable

Cache coherence /1

- Now that cores have their own *private* L1 cache



- … when jobs share data across cores, R/W operations on the *same* memory location may see *different* copies of it in their respective L1 cache

Cache coherence /2

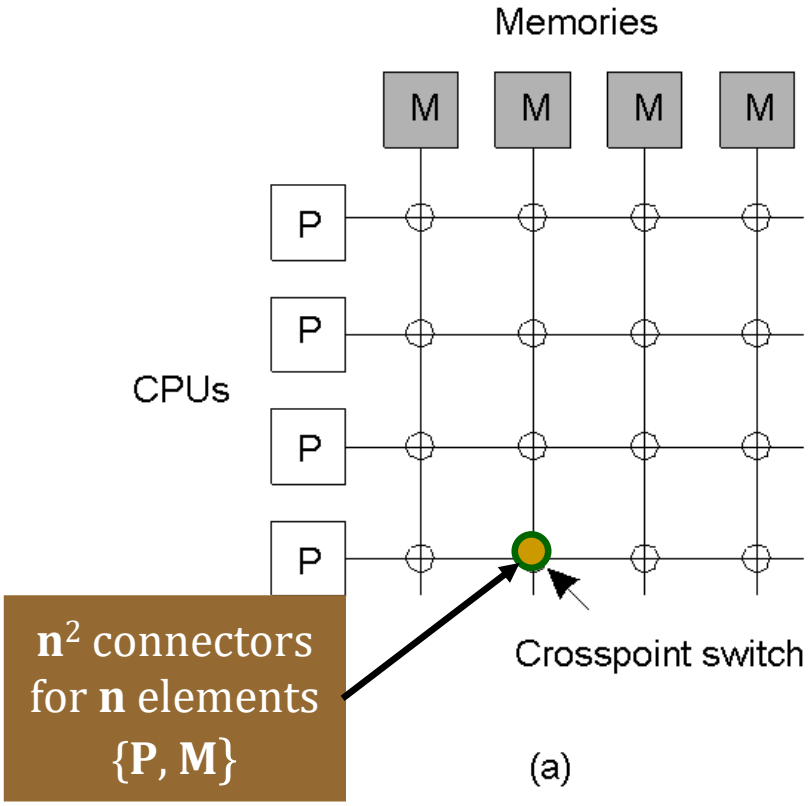
- Naïve thoughts …
  - Renounce caches
    - Nay, that would bog performance
  - Sharing L1 across cores
    - Nay, parallelism would smash locality
  - Use write-through caches
    - Nay, local reads would lose remote writes

- **Req-1**: every read must see the effect of every write
  - Either every write updates every L1 (*write update*)
  - Or every write invalidates all L1 copies (*write invalidate*)
- **Req-2**: all reads must see the same order of writes
  - Write requests' propagation on the bus tells the order (*snooping*)

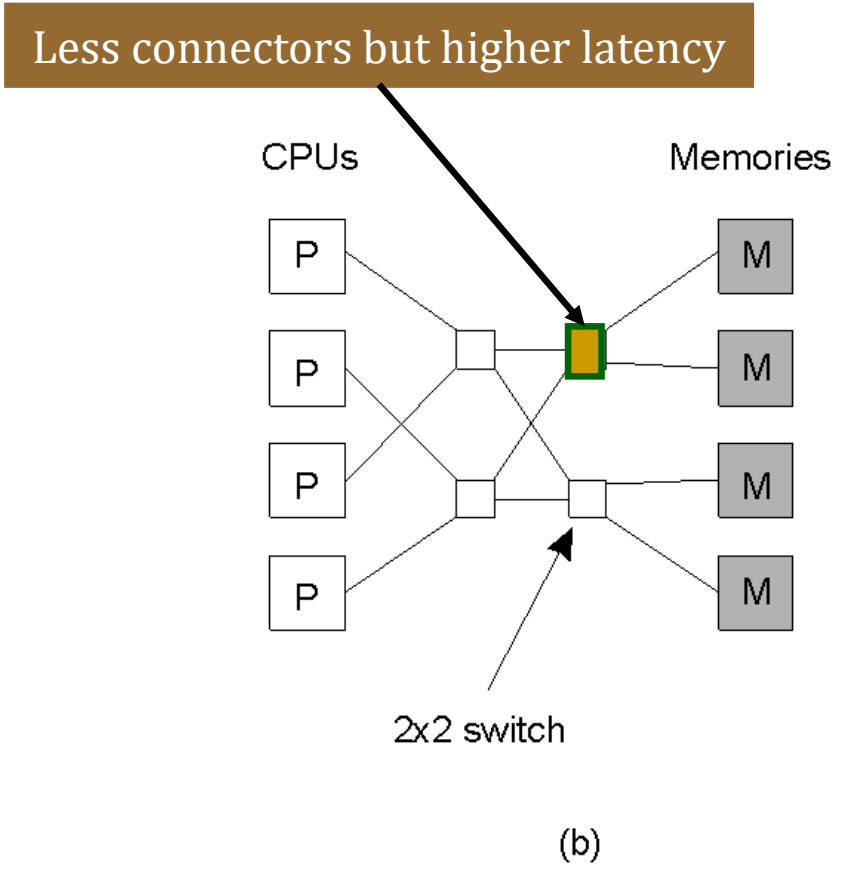
Multiprocessors – 1

- All processors have a single common address space
  - Bus-based P-M communication requires arbitration and becomes a bottleneck
  - Switched P-M communication balances load better but requires far more complex logic
    - Crossbars are efficient but costly
    - Omega networks have cheaper units but are more complex to operate

Multiprocessors – 2



Crossbar switch

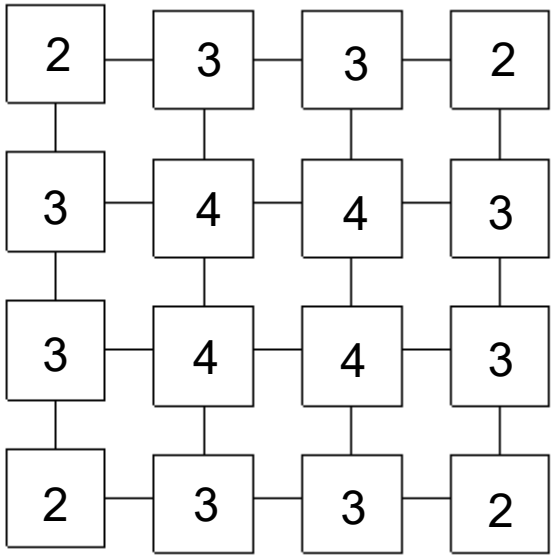


Omega network

Multi-computers

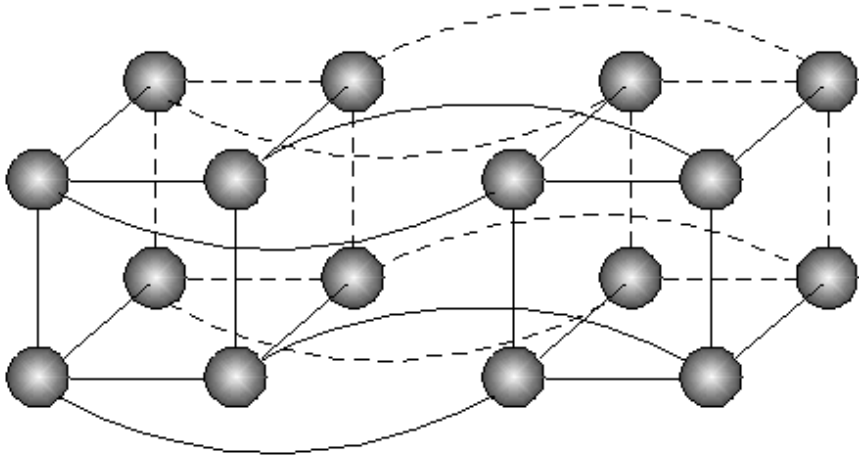
Every node does local processing and routing

2^n nodes
$n2^{n-1}$ links



Grid

Node position determines number of neighbours (position-dependent routing)

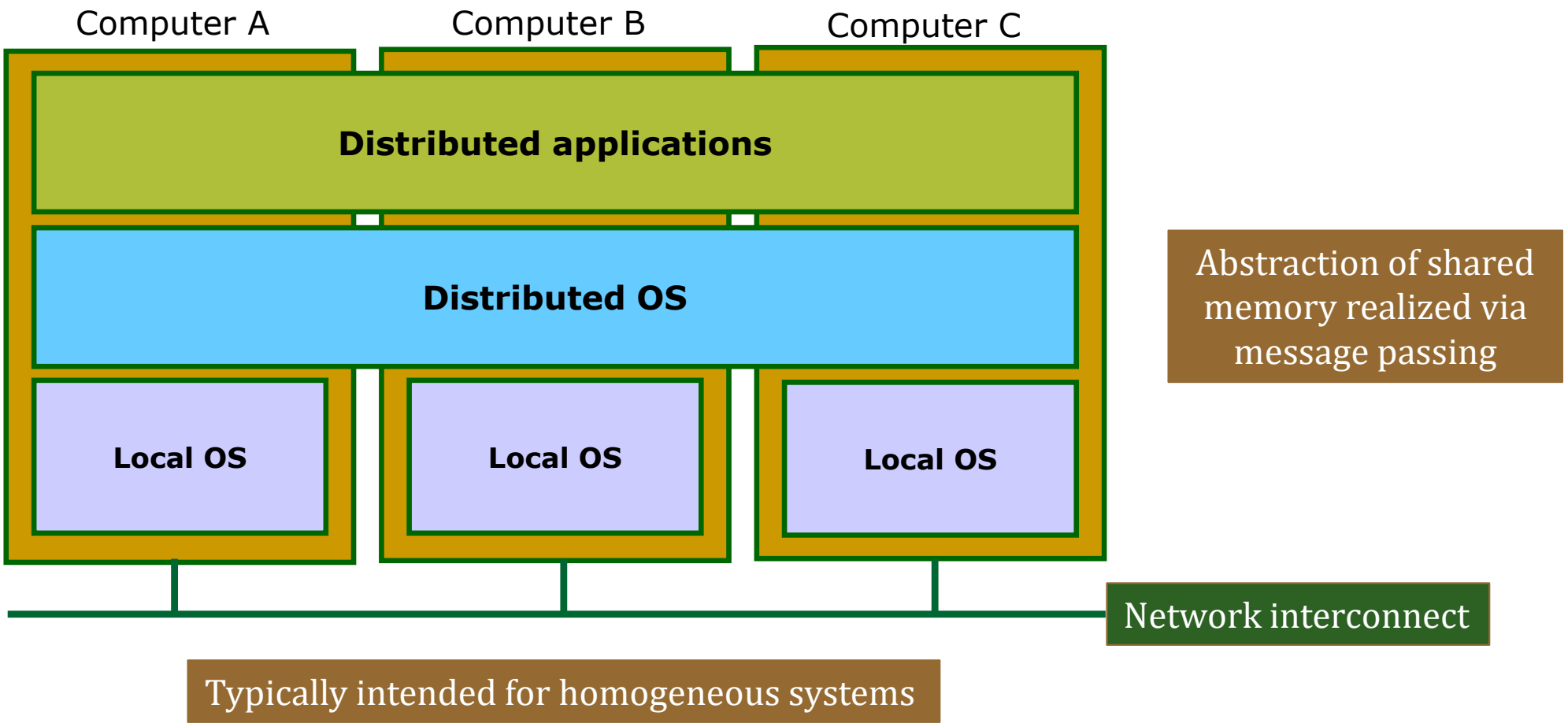


n = 4

Hypercube

Number of neighbours is location independent (and so is routing)

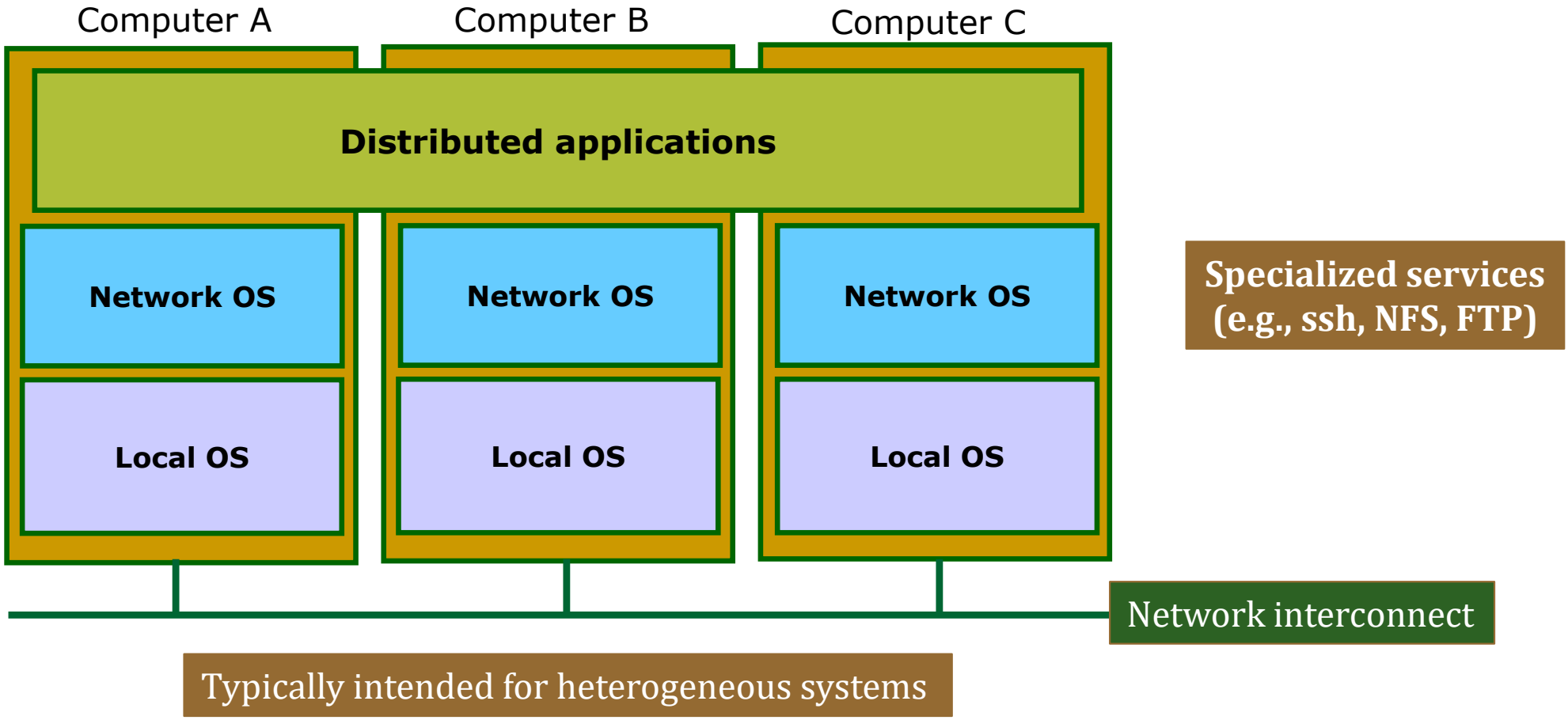
Software distribution – 1



Software distribution – 2

- Programming distributed systems (DS) is *harder* than doing so for multiprocessors (MP)
  - Optimal task scheduling is a hard problem in MP
  - Resource sharing is very costly in DS and may prefer spin locks to suspend locks in MP
- Communicating by shared memory is simpler than by message passing
  - The former is natural in MP
  - The latter scales nicely but suffers from queuing, synchronization, coordination, and network effects
    - Which is why asynchronous comm is preferred in DS

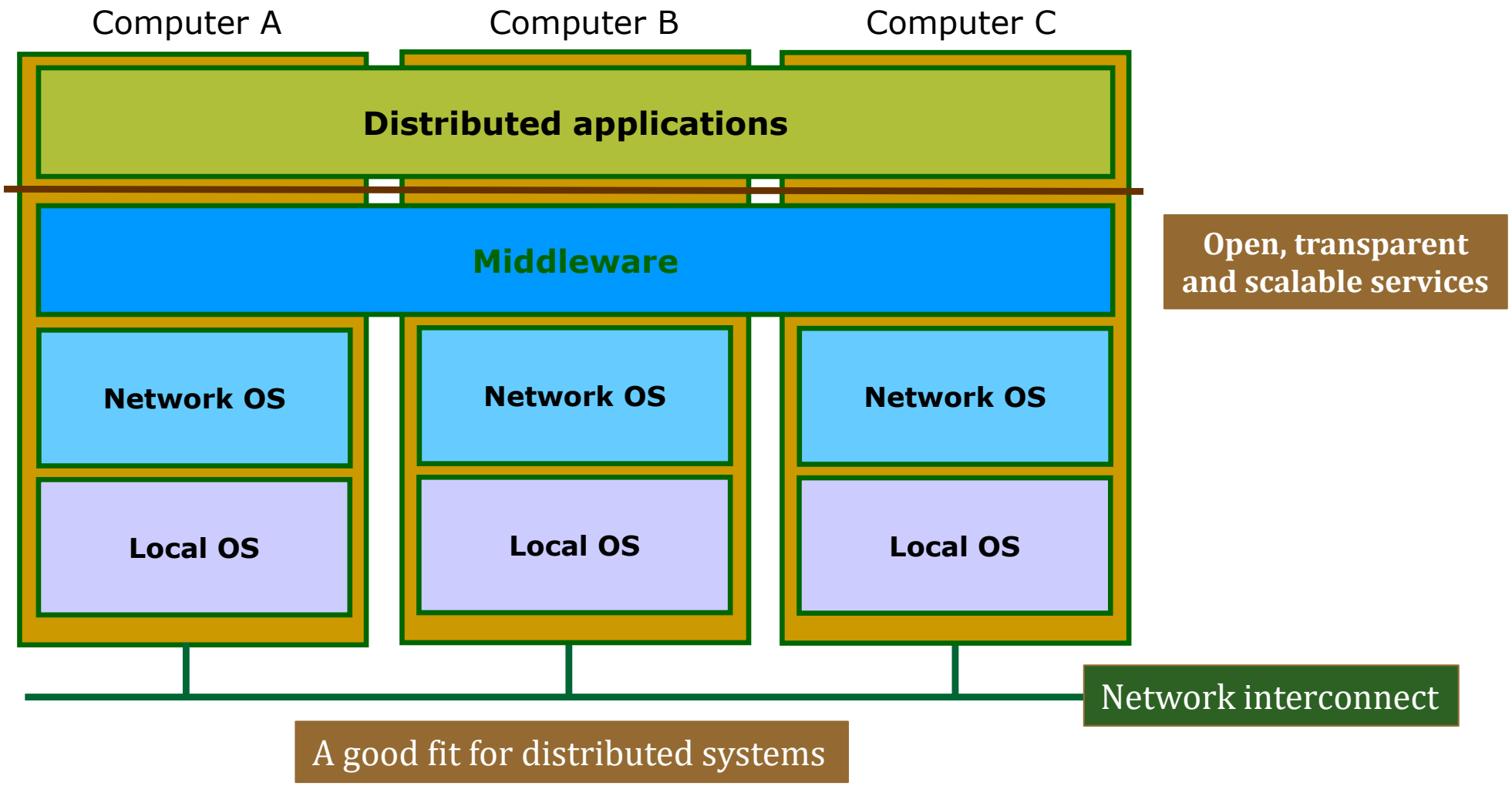
Software distribution – 3



Software distribution – 4

- Neither the distributed OS nor the network OS paradigm conform with the definition of distributed system
  - The former may have good transparency but its participant nodes are **not** independent
  - The latter may have good openness and scalability features but it does **not** yield unitary coherence
- The new means to software distribution is called **middleware**

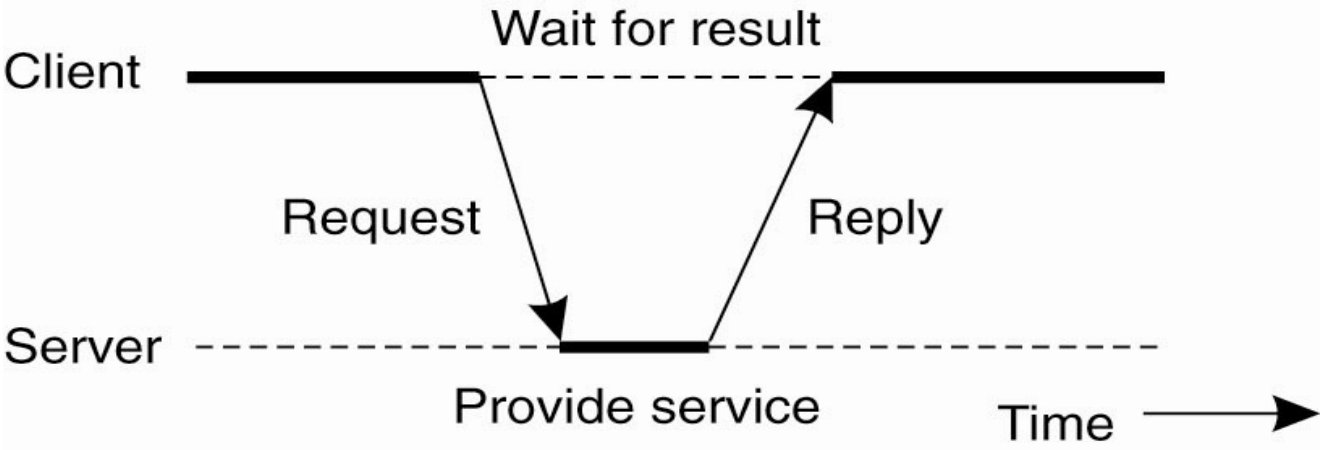
Software distribution – 5



Variants of middleware

- Distributed file system
  - UNIX-like NFS
- Remote procedure call (RPC)
- Distributed objects (RMI)
- Distributed documents: Web 1.0
  - All TCP based
- Distributed everything: Web 2.0 (all over HTTP)
  - Resource-centric: REST
  - Data-centric: GraphQL
  - Collaboration-centric: gRPC
  - Stream-oriented: WebRTC

Styles of distributed interaction – 1

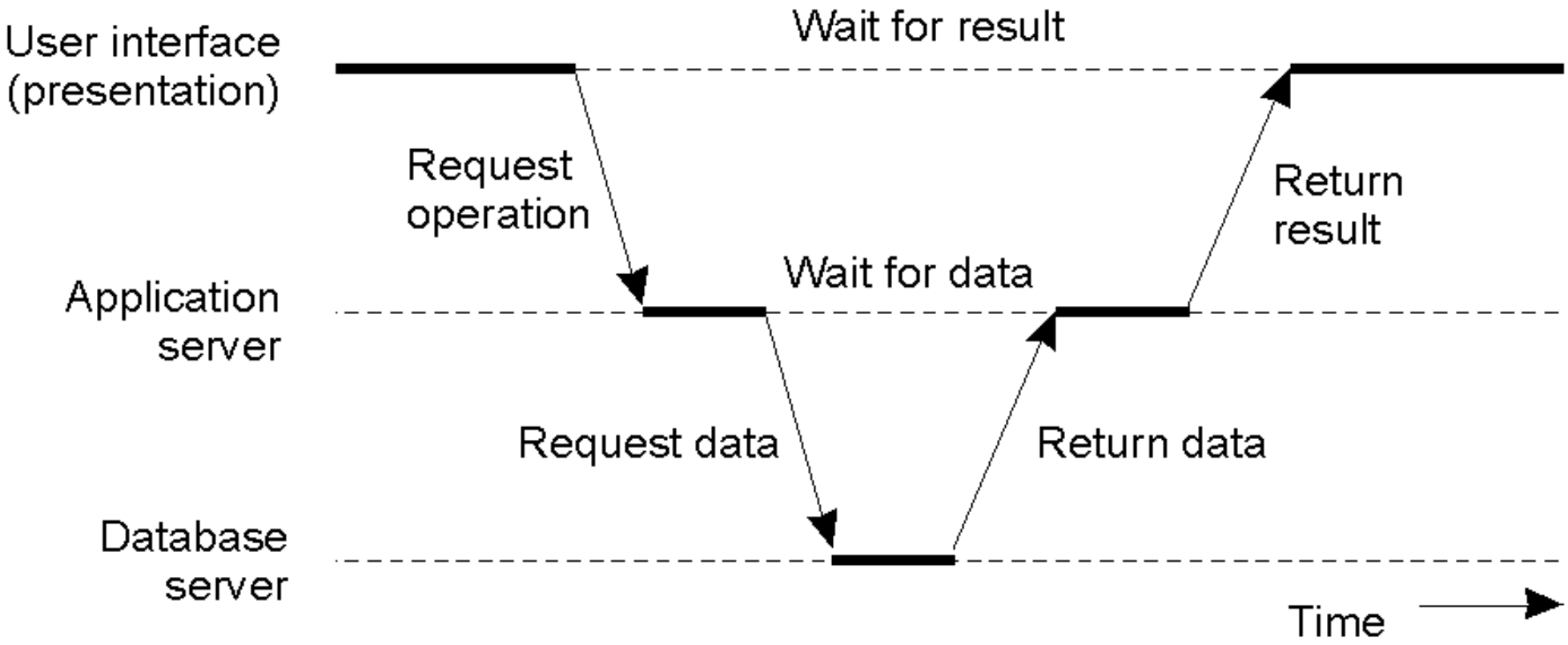


- The **request-reply** style of interaction was the killer factor in the Web 1.0 world
  - Reissuing requests in the absence of replies is harmless *only* for **idempotent** operations
  - Very few operations are so …

Styles of distributed interaction – 2

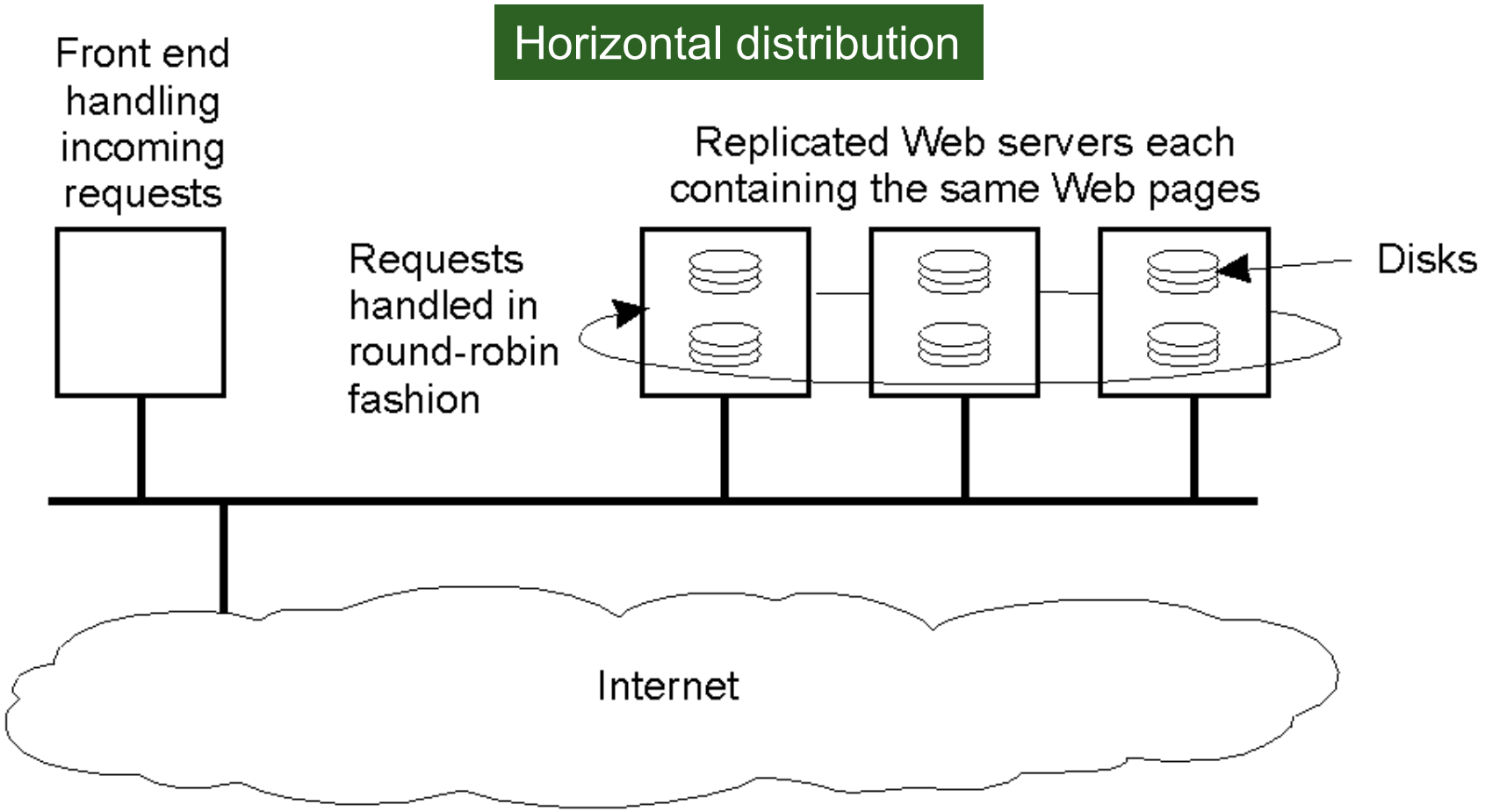
- Client-server architectures vary according to the distribution of either service or data
- Distribution is **vertical** when service is decomposed across multiple authorities
  - Akin to functional pipelining: *specialization*
  - Overall service needs coordination of parts
- Distribution is **horizontal** when data is replicated across multiple identical servers
  - *Replication* is suited for load balancing
  - Consistency must be preserved across replicas

Styles of distributed interaction – 3



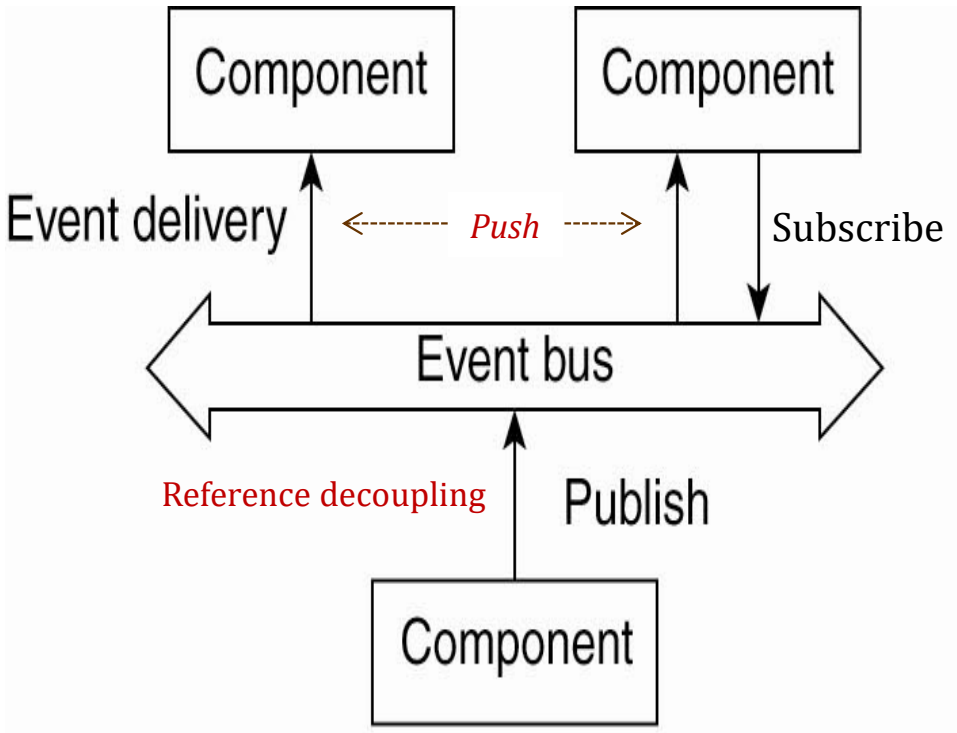
Vertical distribution

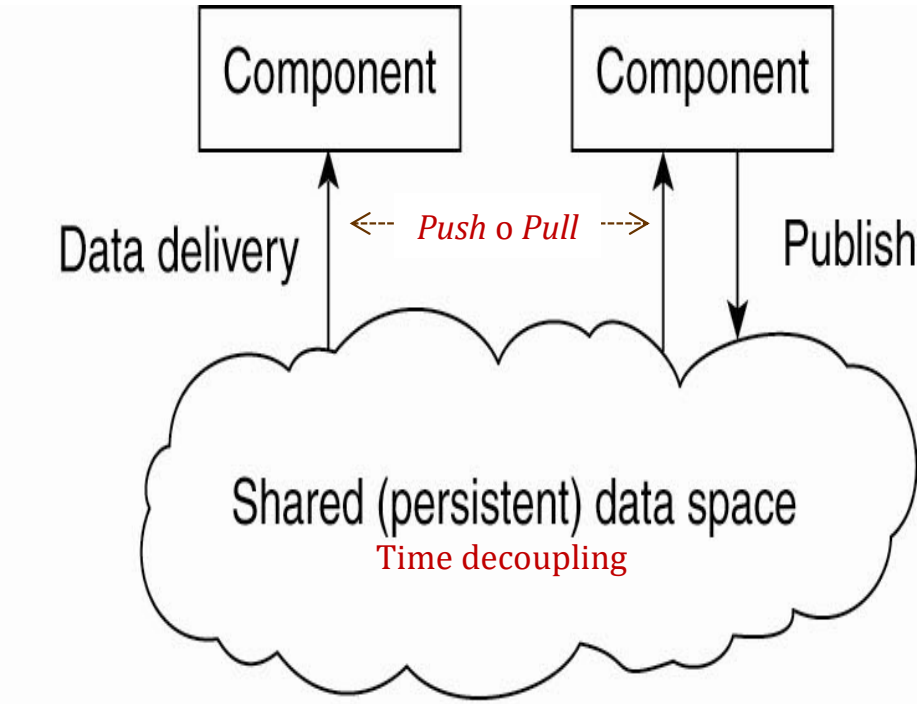
Styles of distributed interaction – 4



Styles of distributed interaction – 5

Beyond client-server





Tanenbaum & Van Steen, *Distributed Systems: Principles and Paradigms*, 2e, (c) 2007 Prentice-Hall, Inc.

Views of a remote call

Tanenbaum & Van Steen, *Distributed Systems: Principles and Paradigms*, 2e, (c) 2007 Prentice-Hall, Inc.