Chapter 1: Introduction

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Distributed Computing: Principles, Algorithms, and Systems

Cambridge University Press

Definition

- Autonomous processors communicating over a communication network
- Some characteristics
    - No common physical clock
    - No shared memory
    - Geographical seperation
    - Autonomy and heterogeneity

Distributed System Model

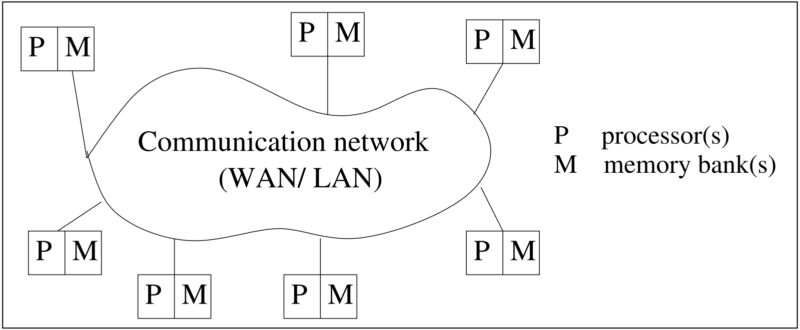


Figure 1.1: A distributed system connects processors by a communication network.

Relation between Software Components

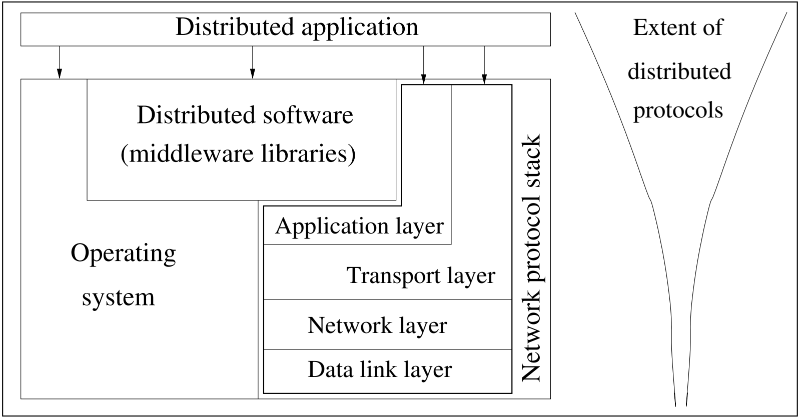


Figure 1.2: Interaction of the software components at each process.

Motivation for Distributed System

- Inherently distributed computation
- Resource sharing
- Access to remote resources
- Increased performance/cost ratio
- Reliability
  - availability, integrity, fault-tolerance
- Scalability
- Modularity and incremental expandability

Parallel Systems

- Multiprocessor systems (direct access to shared memory, UMA model)
  - Interconnection network - bus, multi-stage sweitch
  - E.g., Omega, Butterfly, Clos, Shuffle-exchange networks
  - Interconnection generation function, routing function
- Multicomputer parallel systems (no direct access to shared memory, NUMA model)
  - bus, ring, mesh (w w/o wraparound), hypercube topologies
  - E.g., NYU Ultracomputer, CM* Conneciton Machine, IBM Blue gene
- Array processors (colocated, tightly coupled, common system clock)
  - Niche market, e.g., DSP applications

UMA vs. NUMA Models

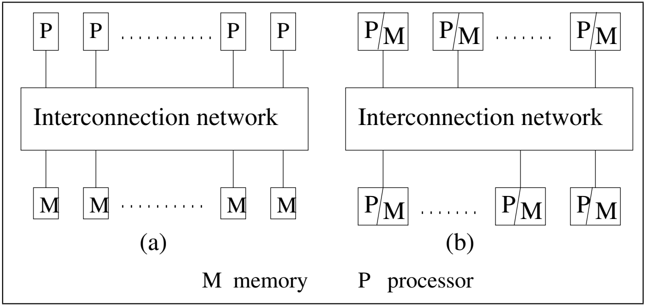


Figure 1.3: Two standard architectures for parallel systems. (a) Uniform memory access (UMA) multiprocessor system. (b) Non-uniform memory access (NUMA) multiprocessor. In both architectures, the processors may locally cache data from memory.

Omega, Butterfly Interconnects

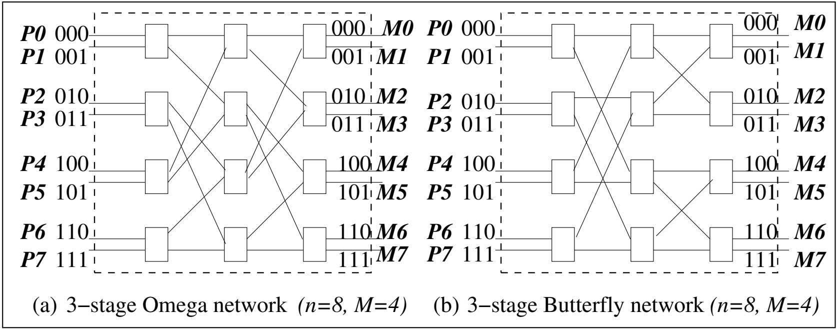


Figure 1.4: Interconnection networks for shared memory multiprocessor systems. (a) Omega network (b) Butterfly network.

Omega Network

- n processors, n memory banks
- $\log n$ stages: with $n/2$ switches of size 2x2 in each stage
- Interconnection function: Output i of a stage connected to input j of next stage:

$$j = \begin{cases} 2i & \text{for } 0 \leq i \leq n/2 - 1 \\ 2i + 1 - n & \text{for } n/2 \leq i \leq n - 1 \end{cases}$$

- Routing function: in any stage s at any switch:
  to route to dest. j,
  if $s + 1$th MSB of $j = 0$ then route on upper wire
  else [$s + 1$th MSB of $j = 1$] then route on lower wire

Interconnection Topologies for Multiprocesors

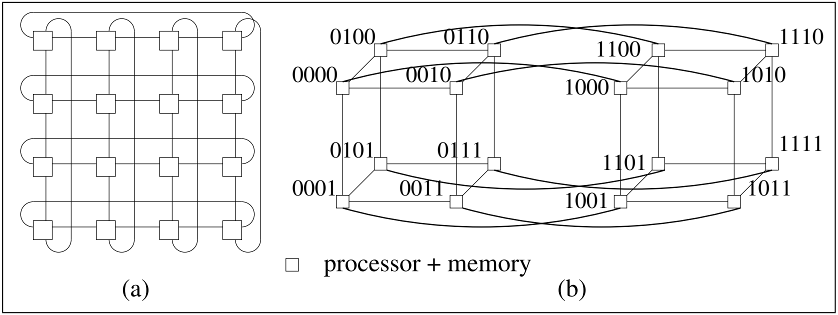


Figure 1.5: (a) 2-D Mesh with wraparound (a.k.a. torus) (b) 3-D hypercube

Flynn's Taxonomy

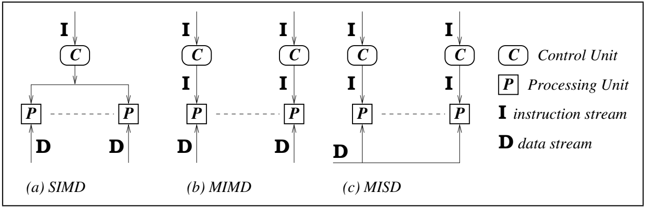


Figure 1.6: SIMD, MISD, and MIMD modes.

- SISD: Single Instruction Stream Single Data Stream (traditional)
- SIMD: Single Instruction Stream Multiple Data Stream
  - scientific applicaitons, applications on large arrays
  - vector processors, systolic arrays, Pentium/SSE, DSP chips
- MISD: Multiple Instruciton Stream Single Data Stream
  - E.g., visualization
- MIMD: Multiple Instruction Stream Multiple Data Stream
  - distributed systems, vast majority of parallel systems

Terminology

- Coupling
  - Interdependency/binding among modules, whether hardware or software (e.g., OS, middleware)
- Parallelism: $T(1)/T(n)$.
  - Function of program and system
- Concurrency of a program
  - Measures productive CPU time vs. waiting for synchronization operations
- Granularity of a program
  - Amt. of computation vs. amt. of communication
  - Fine-grained program suited for tightly-coupled system

Message-passing vs. Shared Memory

- Emulating MP over SM:
  - Partition shared address space
  - Send/Receive emulated by writing/reading from special mailbox per pair of processes
- Emulating SM over MP:
  - Model each shared object as a process
  - Write to shared object emulated by sending message to owner process for the object
  - Read from shared object emulated by sending query to owner of shared object

Classification of Primitives (1)

- Synchronous (send/receive)
  - Handshake between sender and receiver
  - Send completes when Receive completes
  - Receive completes when data copied into buffer
- Asynchronous (send)
  - Control returns to process when data copied out of user-specified buffer

Classification of Primitives (2)

- Blocking (send/receive)
  - Control returns to invoking process after processing of primitive (whether sync or async) completes
- Nonblocking (send/receive)
  - Control returns to process immediately after invocation
  - Send: even before data copied out of user buffer
  - Receive: even before data may have arrived from sender

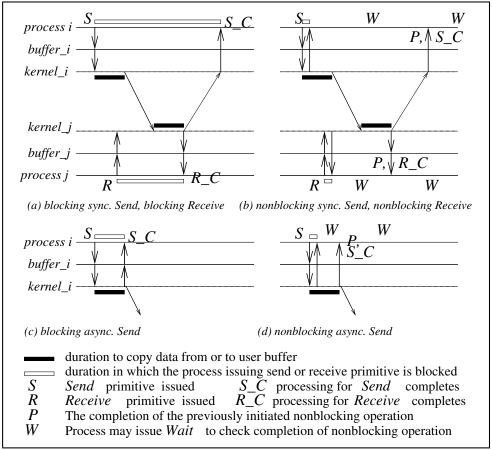
Non-blocking Primitive

```
$Send(X, destination, handle_k)$                          //$handle_k$ is a return parameter
...
...
$Wait(handle_1, handle_2, \ldots, handle_k, \ldots, handle_m)$          //$Wait$ always blocks
```

Figure 1.7: A nonblocking *send* primitive. When the *Wait* call returns, at least one of its parameters is posted.

- Return parameter returns a system-generated handle
  - Use later to check for status of completion of call
  - Keep checking (loop or periodically) if handle has been posted
  - Issue Wait(handle1, handle2, ...) call with list of handles
  - Wait call blocks until one of the stipulated handles is posted

Blocking/nonblocking; Synchronous/asynchronous; send/receive primities



(a) blocking sync. Send, blocking Receive

(b) nonblocking sync. Send, nonblocking Receive

(c) blocking async. Send

(d) nonblocking async. Send

Figure 1.8:Illustration of 4 send and 2 receive primitives

Asynchronous Executions; Mesage-passing System

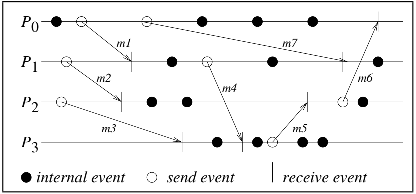


Figure 1.9: Asynchronous execution in a message-passing system

Synchronous Executions: Message-passing System

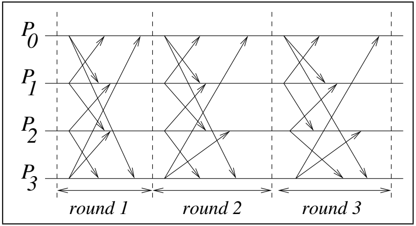


Figure 1.10: Synchronous execution in a message-passing system

In any round/step/phase: $(send \mid internal)^*(receive \mid internal)*$

```
$Sync\_Execution$(int $k$, $n$) //$k$ rounds, $n$ processes.
    for $r = 1$ to $k$ do
        proc $i$ sends msg to $(i+1)$ mod $n$ and $(i-1)$ mod $n$;
        each proc $i$ receives msg from $(i+1)$ mod $n$ and $(i-1)$ mod $n$;
        compute app-specific function on received values.
```

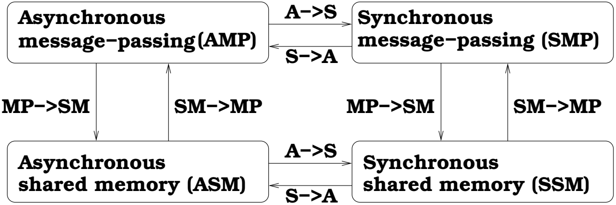
Synchronous vs. Asynchronous Executions (1)

- Sync vs async processors; Sync vs async primitives
- Sync vs async executions
- Async execution
    - No processor synchrony, no bound on drift rate of clocks
    - Message delays finite but unbounded
    - No bound on time for a step at a process
- Sync execution
    - Processors are synchronized; clock drift rate bounded
    - Message delivery occurs in one logical step/round
    - Known upper bound on time to execute a step at a process

Synchronous vs. Asynchronous Executions (2)

- Difficult to build a truly synchronous system; can simulate this abstraction
- Virtual synchrony:
    - async execution, processes synchronize as per application requirement;
    - execute in rounds/steps
- Emulations:
    - Async program on sync system: trivial (A is special case of S)
    - Sync program on async system: tool called *synchronizer*

System Emulations



Asynchronous message−passing (AMP)

A−>S

S−>A

Synchronous message−passing (SMP)

MP−>SM

SM−>MP

MP−>SM

SM−>MP

Asynchronous shared memory (ASM)

A−>S

S−>A

Synchronous shared memory (SSM)

Figure 1.11: Sync ↔ async, and shared memory ↔ msg-passing emulations

- Assumption: failure-free system
- System A emulated by system B:
  - If not solvable in B, not solvable in A
  - If solvable in A, solvable in B

Challenges: System Perspective (1)

- Communication mechanisms: E.g., Remote Procedure Call (RPC), remote object invocation (ROI), message-oriented vs. stream-oriented communication
- Processes: Code migration, process/thread management at clients and servers, design of software and mobile agents
- Naming: Easy to use identifiers needed to locate resources and processes transparently and scalably
- Synchronization
- Data storage and access
  - Schemes for data storage, search, and lookup should be fast and scalable across network
  - Revisit file system design
- Consistency and replication
  - Replication for fast access, scalability, avoid bottlenecks
  - Require consistency management among replicas

Challenges: System Perspective (2)

- Fault-tolerance: correct and efficient operation despite link, node, process failures
- Distributed systems security
    - Secure channels, access control, key management (key generation and key distribution), authorization, secure group management
- Scalability and modularity of algorithms, data, services
- Some experimental systems: Globe, Globus, Grid

Challenges: System Perspective (3)

- API for communications, services: ease of use
- Transparency: hiding implementation policies from user
  - Access: hide differences in data rep across systems, provide uniform operations to access resources
  - Location: locations of resources are transparent
  - Migration: relocate resources without renaming
  - Relocation: relocate resources as they are being accessed
  - Replication: hide replication from the users
  - Concurrency: mask the use of shared resources
  - Failure: reliable and fault-tolerant operation

Challenges: Algorithm/Design (1)

- Useful execution models and frameworks: to reason with and design correct distributed programs
    - Interleaving model
    - Partial order model
    - Input/Output automata
    - Temporal Logic of Actions
- Dynamic distributed graph algorithms and routing algorithms
    - System topology: distributed graph, with only local neighborhood knowledge
    - Graph algorithms: building blocks for group communication, data dissemination, object location
    - Algorithms need to deal with dynamically changing graphs
    - Algorithm efficiency: also impacts resource consumption, latency, traffic, congestion

Challenges: Algorithm/Design (2)

- Time and global state
    - 3D space, 1D time
    - Physical time (clock) accuracy
    - Logical time captures inter-process dependencies and tracks relative time progression
    - Global state observation: inherent distributed nature of system
    - Concurrency measures: concurrency depends on program logic, execution speeds within logical threads, communication speeds

Challenges: Algorithm/Design (3)

- Synchronization/coordination mechanisms
  - Physical clock synchronization: hardware drift needs correction
  - Leader election: select a distinguished process, due to inherent symmetry
  - Mutual exclusion: coordinate access to critical resources
  - Distributed deadlock detection and resolution: need to observe global state; avoid duplicate detection, unnecessary aborts
  - Termination detection: global state of quiescence; no CPU processing and no in-transit messages
  - Garbage collection: Reclaim objects no longer pointed to by any process

Challenges: Algorithm/Design (4)

- Group communication, multicast, and ordered message delivery
  - Group: processes sharing a context, collaborating
  - Multiple joins, leaves, fails
  - Concurrent sends: semantics of delivery order
- Monitoring distributed events and predicates
  - Predicate: condition on global system state
  - Debugging, environmental sensing, industrial process control, analyzing event streams
- Distributed program design and verification tools
- Debugging distributed programs

Challenges: Algorithm/Design (5)

- Data replication, consistency models, and caching
    - Fast, scalable access;
    - coordinate replica updates;
    - optimize replica placement
- World Wide Web design: caching, searching, scheduling
    - Global scale distributed system; end-users
    - Read-intensive; prefetching over caching
    - Object search and navigation are resource-intensive
    - User-perceived latency

Challenges: Algorithm/Design (6)

- Distributed shared memory abstraction
    - Wait-free algorithm design: process completes execution, irrespective of actions of other processes, i.e., $n-1$ fault-resilience
    - Mutual exclusion
        - Bakery algorithm, semaphores, based on atomic hardware primitives, fast algorithms when contention-free access
    - Register constructions
        - Revisit assumptions about memory access
        - What behavior under concurrent unrestricted access to memory? Foundation for future architectures, decoupled with technology (semiconductor, biocomputing, quantum . . .)
    - Consistency models:
        - coherence versus access cost trade-off
        - Weaker models than strict consistency of uniprocessors

Challenges: Algorithm/Design (7)

- Reliable and fault-tolerant distributed systems
  - Consensus algorithms: processes reach agreement in spite of faults (under various fault models)
  - Replication and replica management
  - Voting and quorum systems
  - Distributed databases, commit: ACID properties
  - Self-stabilizing systems: "illegal" system state changes to "legal" state; requires built-in redundancy
  - Checkpointing and recovery algorithms: roll back and restart from earlier "saved" state
  - Failure detectors:
    - Difficult to distinguish a "slow" process/message from a failed process/ never sent message
    - algorithms that "suspect" a process as having failed and converge on a determination of its up/down status

Challenges: Algorithm/Design (8)

- Load balancing: to reduce latency, increase throughput, dynamically. E.g., server farms
    - Computation migration: relocate processes to redistribute workload
    - Data migration: move data, based on access patterns
    - Distributed scheduling: across processors
- Real-time scheduling: difficult without global view, network delays make task harder
- Performance modeling and analysis: Network latency to access resources must be reduced
    - Metrics: theoretical measures for algorithms, practical measures for systems
    - Measurement methodologies and tools

Applications and Emerging Challenges (1)

- Mobile systems
  - Wireless communication: unit disk model; broadcast medium (MAC), power management etc.
  - CS perspective: routing, location management, channel allocation, localization and position estimation, mobility management
  - Base station model (cellular model)
  - Ad-hoc network model (rich in distributed graph theory problems)
- Sensor networks: Processor with electro-mechanical interface
- Ubiquitous or pervasive computing
  - Processors embedded in and seamlessly pervading environment
  - Wireless sensor and actuator mechanisms; self-organizing; network-centric, resource-constrained
  - E.g., intelligent home, smart workplace

Applications and Emerging Challenges (2)

- Peer-to-peer computing
  - No hierarchy; symmetric role; self-organizing; efficient object storage and lookup;scalable; dynamic reconfig
- Publish/subscribe, content distribution
  - Filtering information to extract that of interest
- Distributed agents
  - Processes that move and cooperate to perform specific tasks; coordination, controlling mobility, software design and interfaces
- Distributed data mining
  - Extract patterns/trends of interest
  - Data not available in a single repository

Applications and Emerging Challenges (3)

- Grid computing
  - Grid of shared computing resources; use idle CPU cycles
  - Issues: scheduling, QOS guarantees, security of machines and jobs
- Security
  - Confidentiality, authentication, availability in a distributed setting
  - Manage wireless, peer-to-peer, grid environments
    - Issues: e.g., Lack of trust, broadcast media, resource-constrained, lack of structure