Definition of a Distributed System

A distributed system is

a collection of independent computers
that appears to its users
as a single coherent system.

... or ...
as a single system.

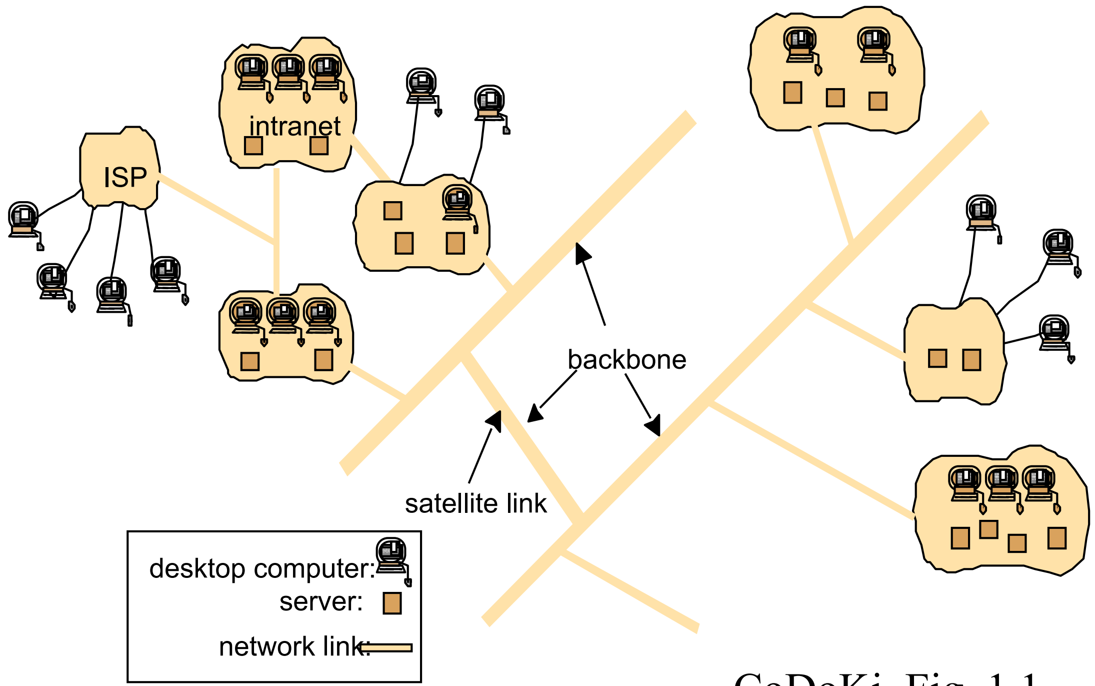
Examples of Distributed Systems

The Internet: net of nets

global access to “everybody”

(data, service, other actor; open ended)

- enormous size (open ended)
- no single authority
- communication types
  - interrogation, announcement, stream
  - data, audio, video



CoDoKi, Fig. 1.1

Figure 1.1 A typical portion of the Internet

Examples of Distributed Systems

Intranets (CoDoKi, Fig. 1.2)

- a single authority
- protected access
  - a firewall
  - total isolation
- may be worldwide
- typical services:
  - infrastructure services: file service, name service
  - application services

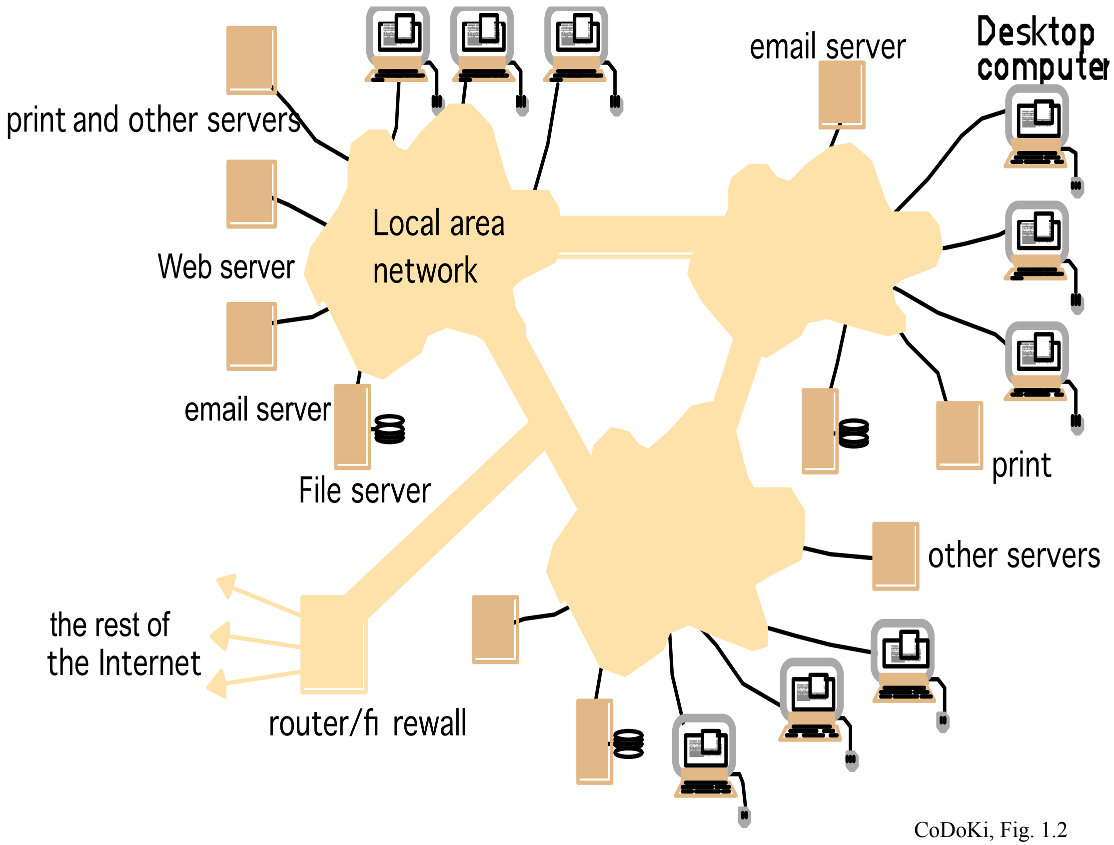


Figure 1.2 A typical intranet

Examples of Distributed Systems

Mobile and ubiquitous computing (CoDoKi Fig 1.3)

- Portable devices
  - laptops
  - handheld devices
  - wearable devices
  - devices embedded in appliances
- Mobile computing
- Location-aware computing
- Ubiquitous computing, pervasive computing

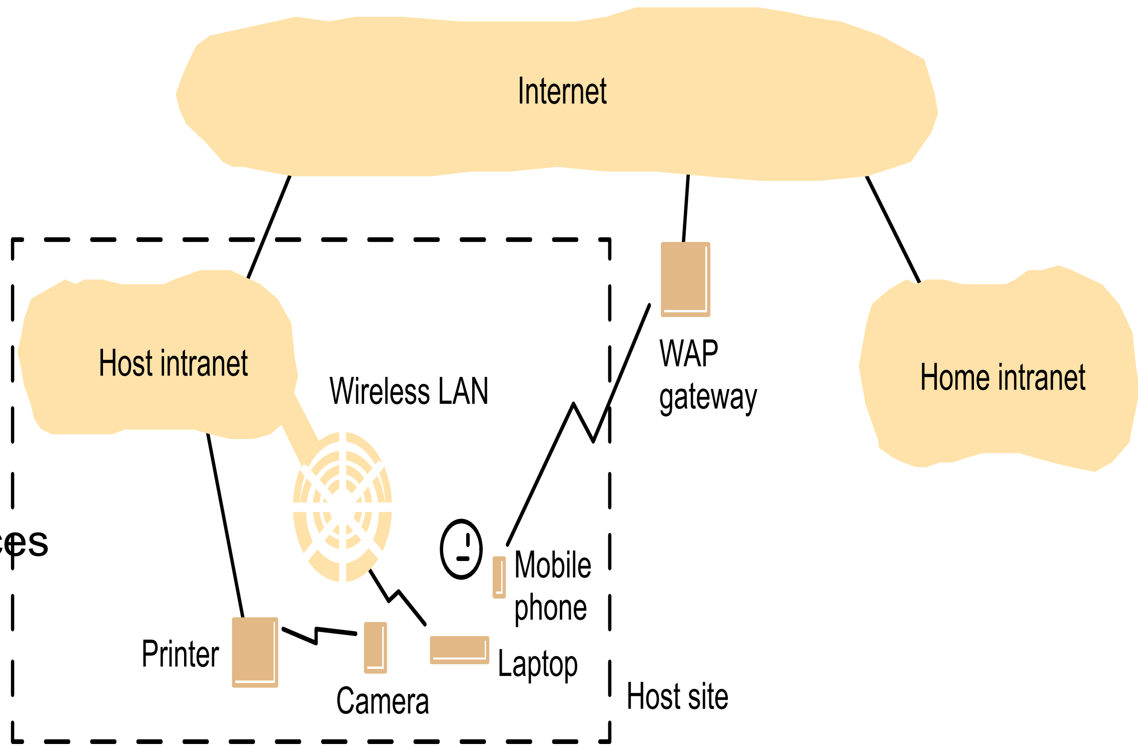
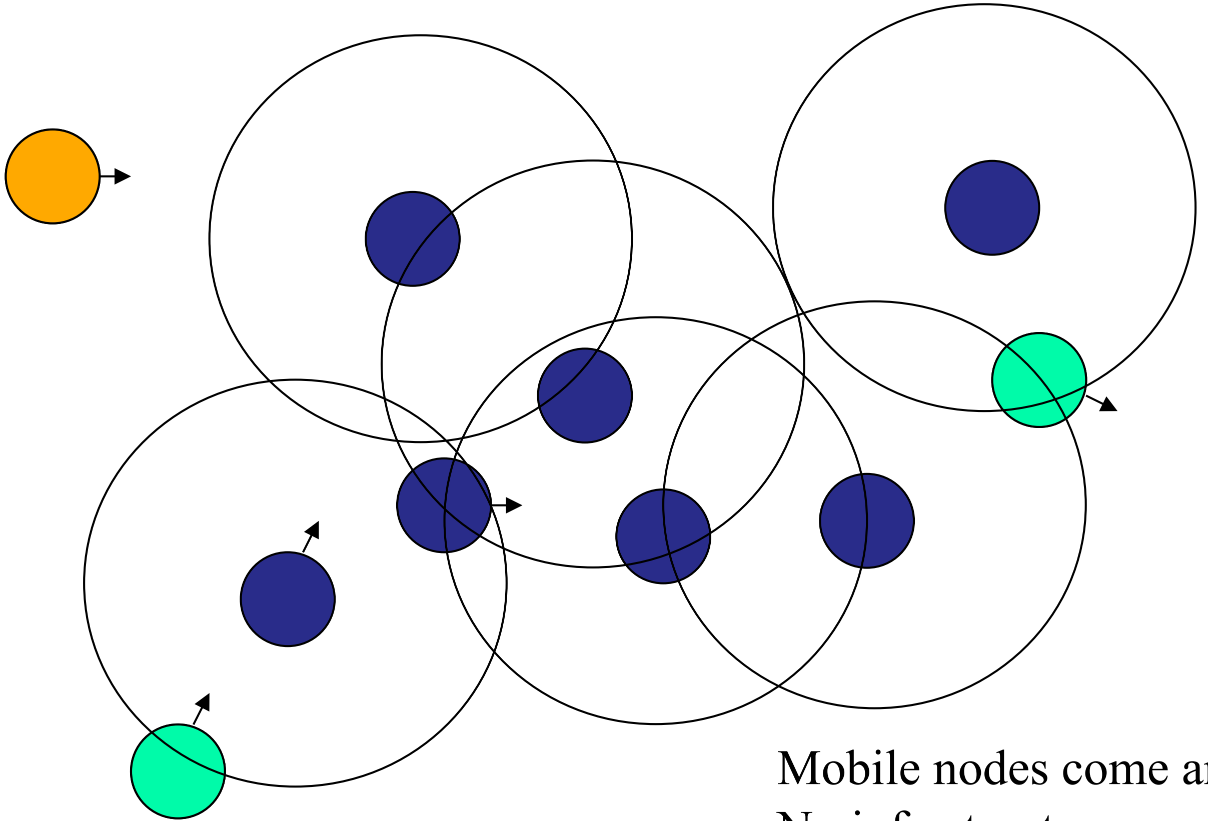


Figure 1.3 Portable and handheld devices in a distributed system

CoDoKi, Fig. 1.3

Mobile Ad Hoc -Networks



Mobile nodes come and go
No infrastructure
- wireless data communication
- multihop networking
- long, nondeterministic dc delays

Problems, e.g.:
- reliable multicast
- group management

Resource Sharing and the Web

- Hardware resources (reduce costs)
- Data resources (shared usage of information)
- Service resources
  - search engines
  - computer-supported cooperative working
- Service vs. server (node or ***process***)

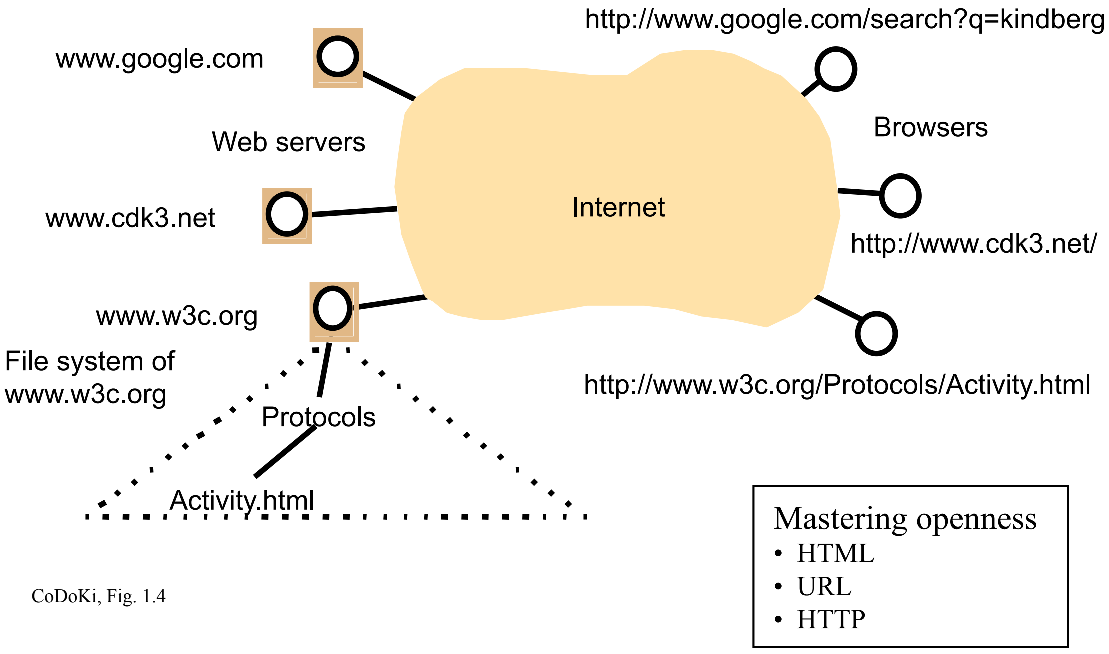
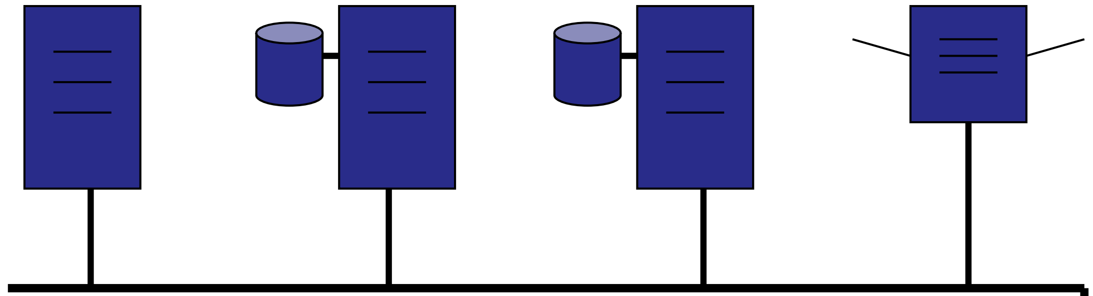
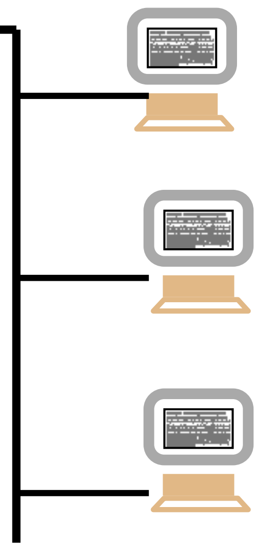


Figure 1.4 Web servers and web browsers

Examples of Distributed Systems, 4



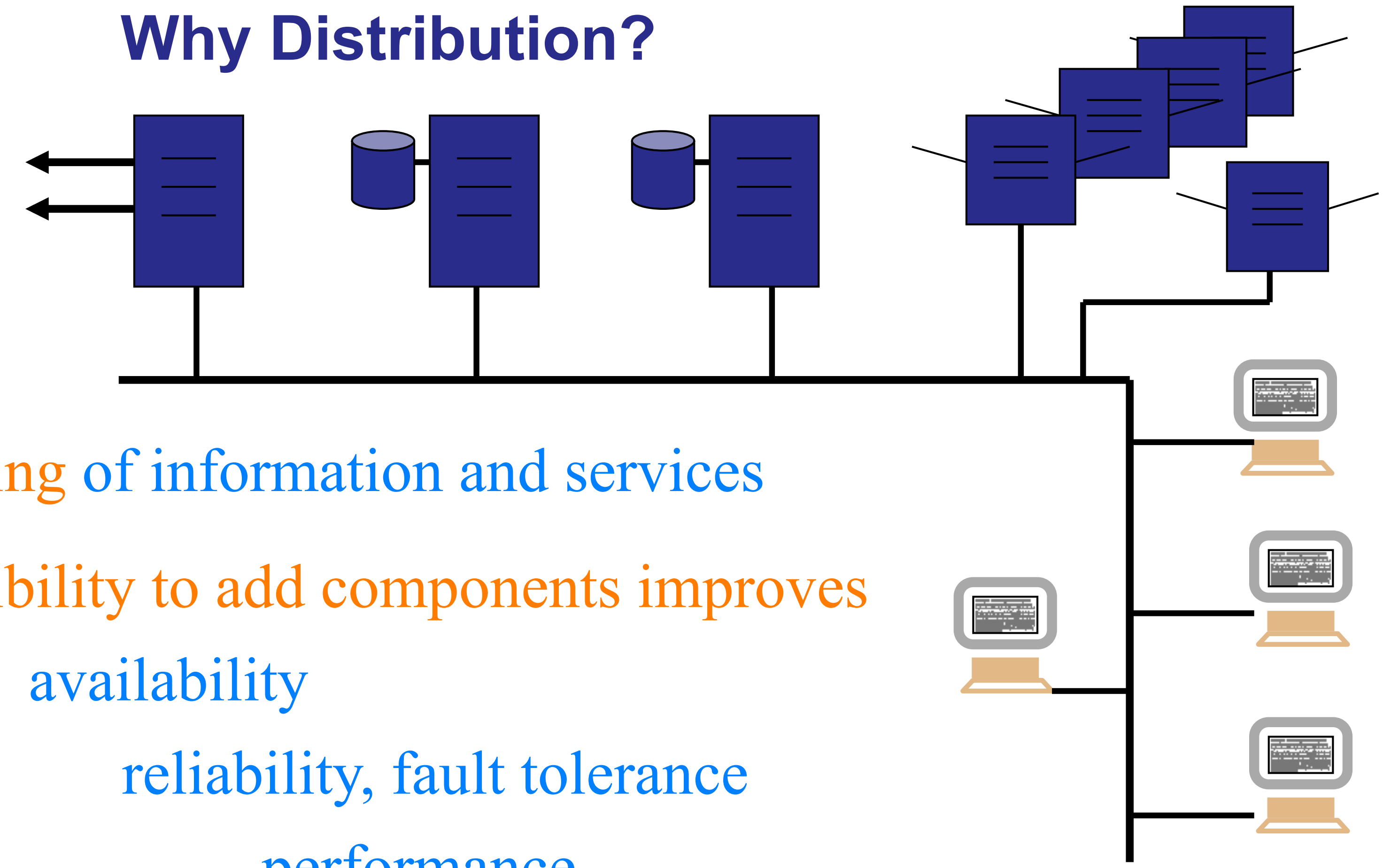


Distributed application

- one single "system"
- one or several autonomous subsystems
- a collection of processors => parallel processing
  => increased performance, reliability, fault tolerance
- partitioned or replicated data
  => increased performance, reliability, fault tolerance

Dependable systems, grid systems, enterprise systems

Why Distribution?



Sharing of information and services

Possibility to add components improves

availability

reliability, fault tolerance

performance

scalability

Facts of life: history, geography, organization

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Goals and challenges for distributed systems

Goals

- Making resources accessible
- Distribution transparency
- Openness
- Scalability
- Security
- System design requirements

Challenges for Making Resources Accessible

- Naming
- Access control
- Security
- Availability
- Performance
- Mutual exclusion of users, fairness
- Consistency in some cases

Challenges for Transparency

- The fundamental idea: a collection of
  - independent, autonomous actors
- Transparency
  - concealment of distribution =>
  - user’s viewpoint: a single unified system

Transparencies

Transparency	Description
Access	Hide differences in data representation and how a resource is accessed
Location	Hide where a resource is located (∗)
Migration	Hide that a resource may move to another location (∗) (the resource does not notice)
Relocation	Hide that a resource may be moved to another location (∗) while in use (the others don't notice)
Replication	Hide that a resource is replicated
Concurrency	Hide that a resource may be shared by several competitive users
Failure	Hide the failure and recovery of a resource
Persistence	Hide whether a (software) resource is in memory or on disk

(∗) Notice the various meanings of ”location” : network address (several layers) ; geographical address

Challenges for Transparencies

- replications and migration cause need for ensuring consistency and distributed decision-making
- failure modes
- concurrency
- heterogeneity

Figure 2.10
Omission and arbitrary failures

Class of failure	*Affects*	*Description*
Fail-stop	Process	Process halts and remains halted. Other processes may detect this state.
Crash	Process	Process halts and remains halted. Other processes may not be able to detect this state.
Omission	Channel	A message inserted in an outgoing message buffer never arrives at the other end's incoming message buffer.
Send-omission	Process	A process completes *send*, but the message is not put in its outgoing message buffer.
Receive-omission	Process	A message is put in a process's incoming message buffer, but that process does not receive it.
Arbitrary (Byzantine)	Process or channel	Process/channel exhibits arbitrary behaviour: it may send/transmit arbitrary messages at arbitrary times, commit omissions; a process may stop or take an incorrect step.

Figure 2.11
Timing failures

Class of Failure	*Affects*	*Description*
Clock	Process	Process's local clock exceeds the bounds on its rate of drift from real time.
Performance	Process	Process exceeds the bounds on the interval between two steps.
Performance	Channel	A message's transmission takes longer than the stated bound.

Failure Handling

- More components => increased fault rate
- Increased possibilities
  - more redundancy => more possibilities for fault tolerance
  - no centralized control => no fatal failure
- Issues
  - Detecting failures
  - Masking failures
  - Recovery from failures
  - Tolerating failures
  - Redundancy
- New: partial failures

Concurrency

- Concurrency:
  - Several simultaneous users => integrity of data
    - mutual exclusion
    - synchronization
    - ext: transaction processing in data bases
  - Replicated data: consistency of information?
  - Partitioned data: how to determine the state of the system?
  - Order of messages?

- There is no global clock!

Consistency Maintenance

- Update ...
- Replication ...
- Cache ...
- Failure ...
- Clock ...
- User interface ....

... consistency

Heterogeneity

- Heterogeneity of
  - networks
  - computer hardware
  - operating systems
  - programming languages
  - implementations of different developers
- Portability, interoperability
- Mobile code, adaptability (applets, agents)
- Middleware (CORBA etc)
- Degree of transparency? Latency? Location-based services?

Challenges for Openness

- Openness facilitates
  - interoperability, portability, extensibility, adaptivity
- Activities addresses
  - extensions: new components
  - re-implementations (by independent providers)
- Supported by
  - public interfaces
  - standardized communication protocols

Challenges for Scalability

- Scalability
- The system will remain effective when there is a
- significant increase in
  - number of resources
  - number of users
  - The architecture and the implementation must allow it
  - The algorithms must be efficient under the circumstances to be expected
  - Example: the Internet

Challenges: Scalability (cont.)

- Controlling the cost of physical resources
- Controlling performance loss
- Preventing software resources running out
- Avoiding performance bottlenecks
- Mechanisms (implement functions) & Policies (how to use the mechanisms)
- Scaling solutions
  - asyncronous communication, decreased messaging (e.g., forms)
  - caching (all sorts of hierarchical memories: data is closer to the user → no wait / assumes rather stable data!)
  - distribution i.e. partitioning of tasks or information (domains) (e.g., DNS)

Challenges for Security

- Security: confidentiality, integrity, availability
- Vulnerable components (Fig. 2.14)
  - channels (links <–> end-to-end paths)
  - processes (clients, servers, outsiders)
- Threats
  - information leakage
  - integrity violation
  - denial of service
  - illegitimate usage

CoDoKi, Fig. 2.14

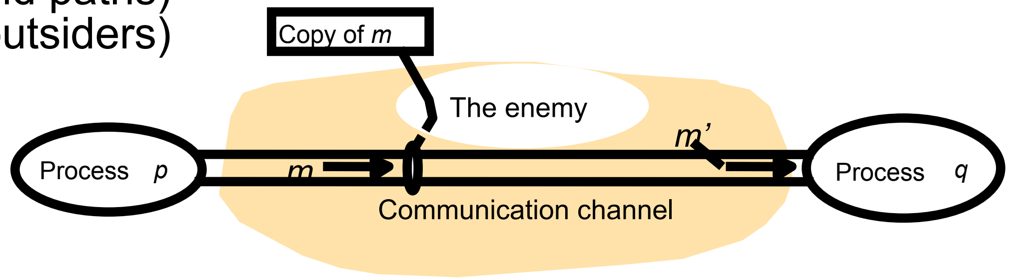


Figure 2.14 The enemy

Current issues:

denial-of-service attacks, security of mobile code, information flow;

open wireless ad-hoc environments

Threats

- Threats to channels (Fig. 2.14)
  - eavesdropping (data, traffic)
  - tampering, replaying
  - masquerading
  - denial of service
- Threats to processes (Fig. 2.13)
  - server: client's identity; client: server's identity
  - unauthorized access (insecure access model)
  - unauthorized information flow (insecure flow model)

CoDoKi, Fig. 2.14

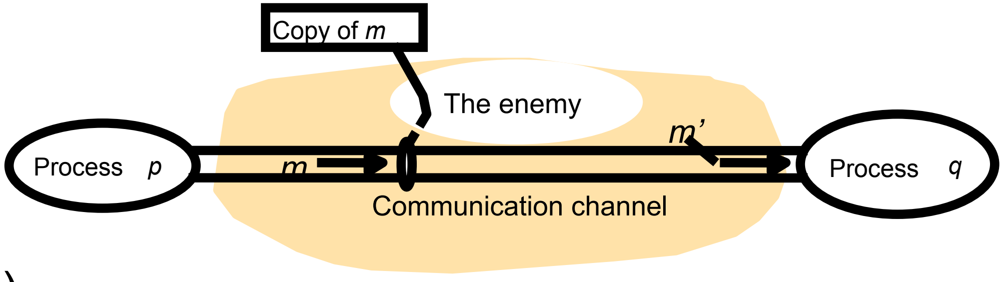
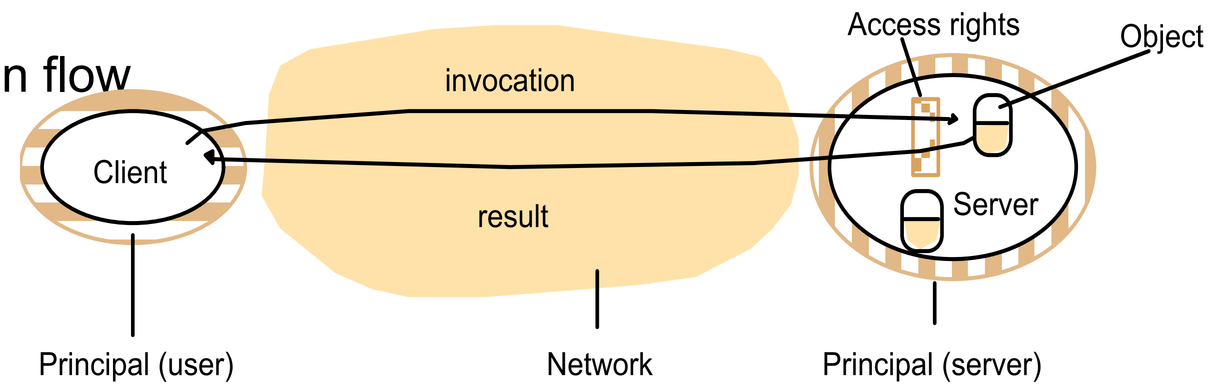


Figure 2.14 The enemy



CoDoKi, Fig. 2.13

Figure 2.13 Objects and principals

Defeating Security Threats

- Techniques
  - cryptography
  - authentication
  - access control techniques
    - intranet: firewalls
    - services, objects: access control lists, capabilities
- Policies
  - access control models
  - lattice models
  - information flow models
- Leads to: secure channels, secure processes, controlled access, controlled flows

Environment challenges

- A distributed system:
  - HW / SW components in different nodes
  - components communicate (using messages)
  - components coordinate actions (using messages)
- Distances between nodes vary
  - in time: from msecs to weeks
  - in space: from mm's to Mm's
  - in dependability
- Autonomous independent actors (=> even independent failures!)

No global clock

Global state information not possible

Challenges: Design Requirements

- Performance issues
  - responsiveness
  - throughput
  - load sharing, load balancing
  - issue: algorithm vs. behavior
- Quality of service
  - correctness (in nondeterministic environments)
  - reliability, availability, fault tolerance
  - security
  - performance
  - adaptability

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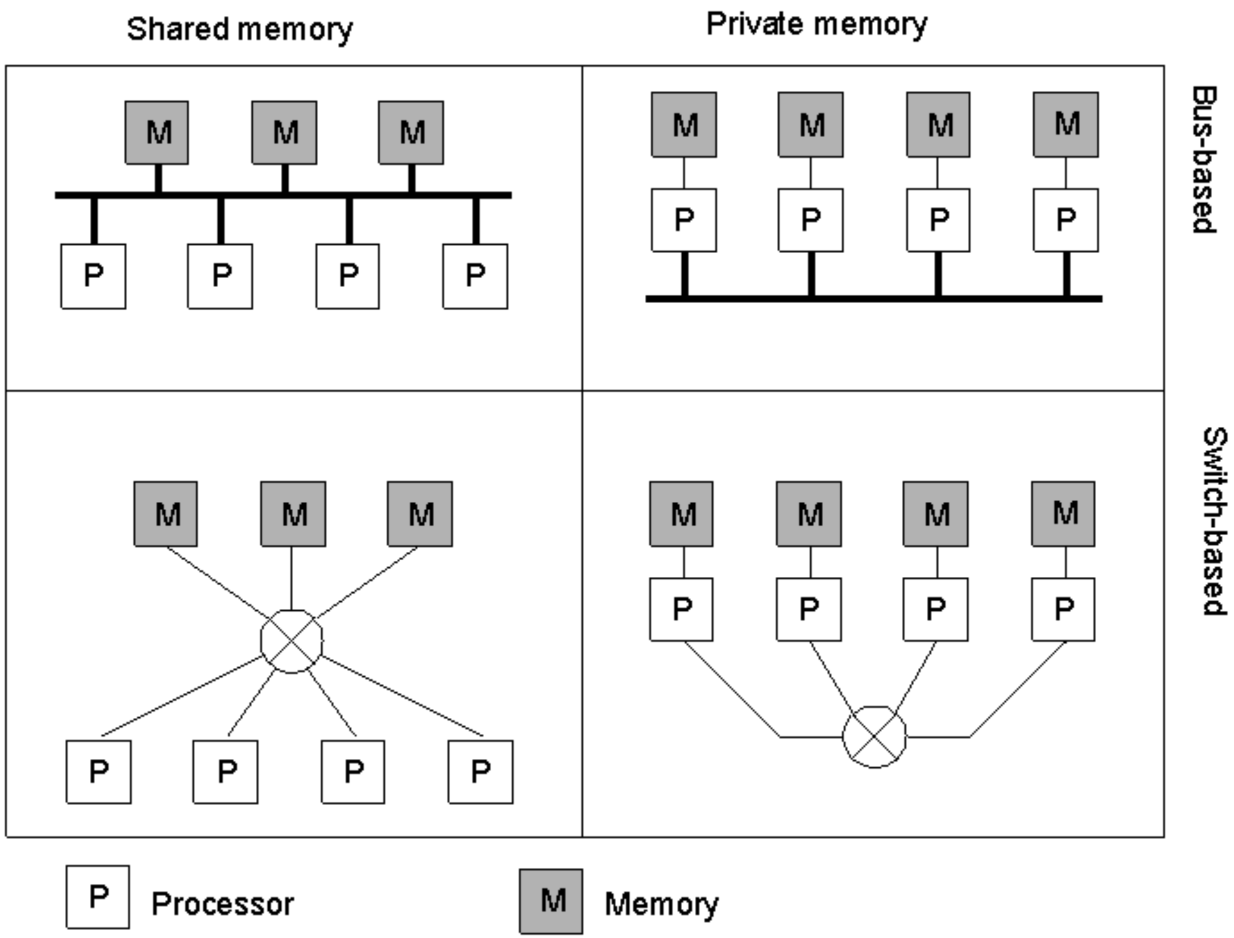
Where is the borderline between a computer and distributed system?

Hardware Concepts

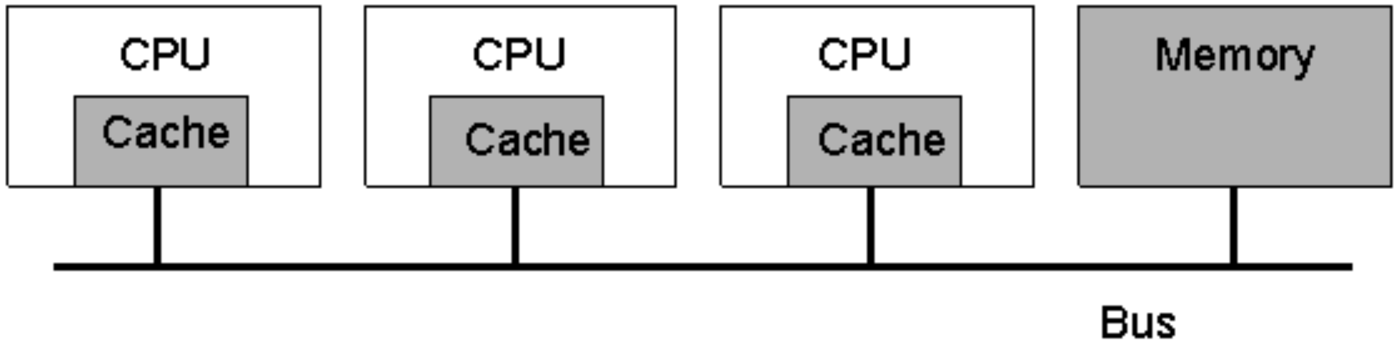
- Characteristics which affect the behavior of software systems
- The platform ....
  - the individual nodes (”computer”, ”processor”)
  - communication between two nodes
  - organization of the system (network of nodes)
- ... and its characteristics
  - capacity of nodes
  - capacity (throughput, delay) of communication links
  - reliability of communication (and of the nodes)
- → Which ways to distribute an application are feasible

Basic Organizations of a Node



1.6 Different basic organizations and memories in distributed computer systems

Multiprocessors (1)

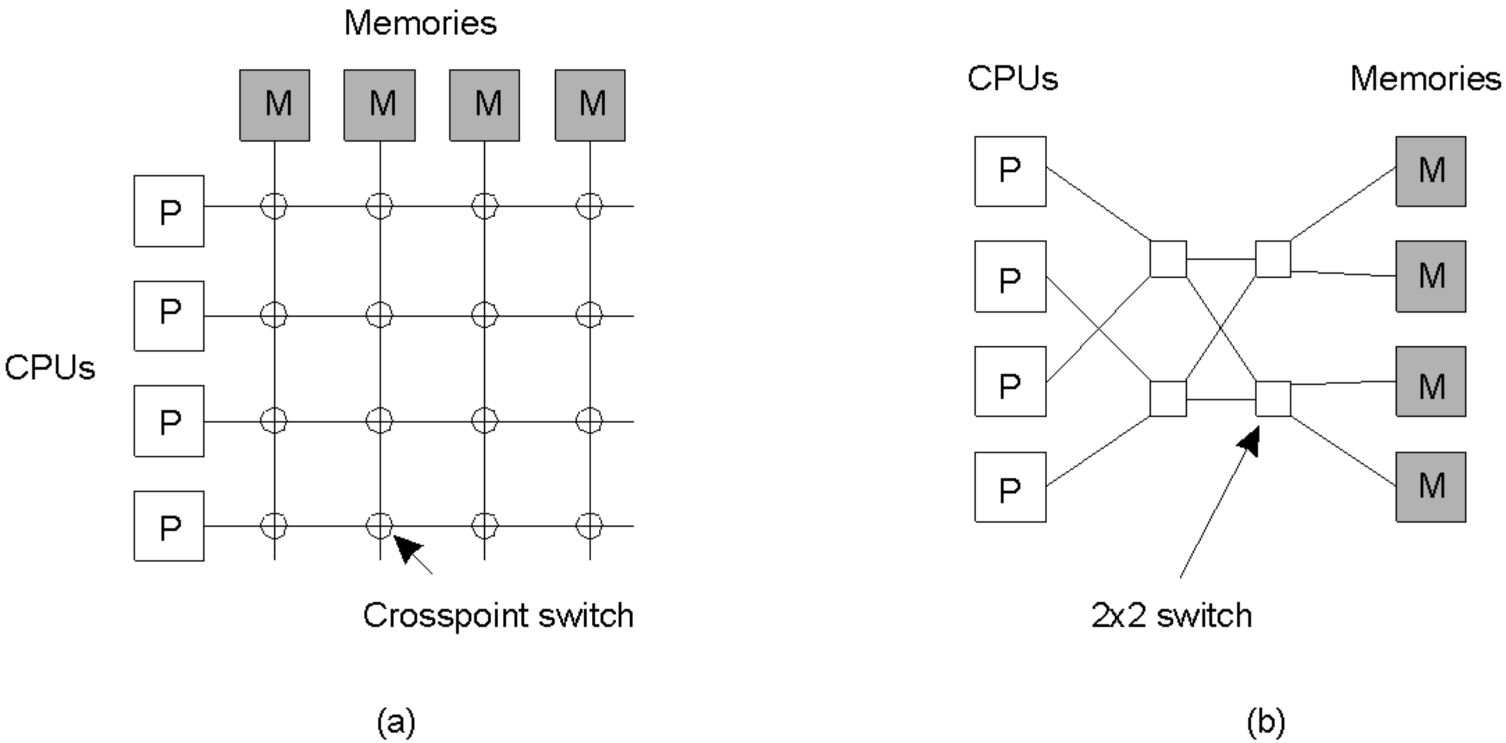


1.7 A bus-based multiprocessor.

Essential characteristics for software design

- fast and reliable communication (shared memory)
  => cooperation at ”instruction level” possible
- bottleneck: memory (especially the ”hot spots”)

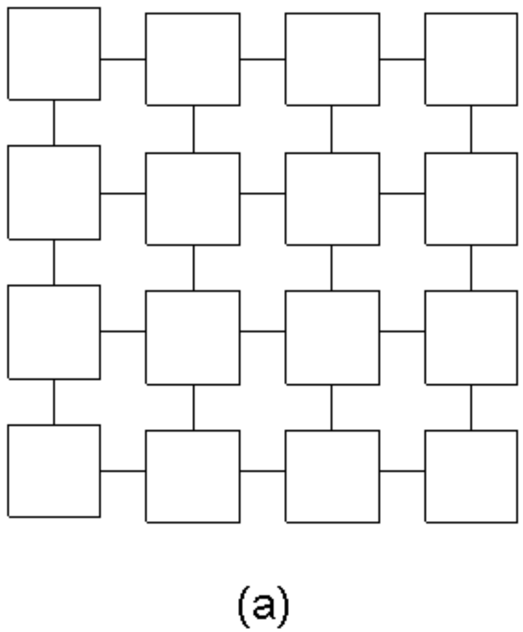
Multiprocessors (2)

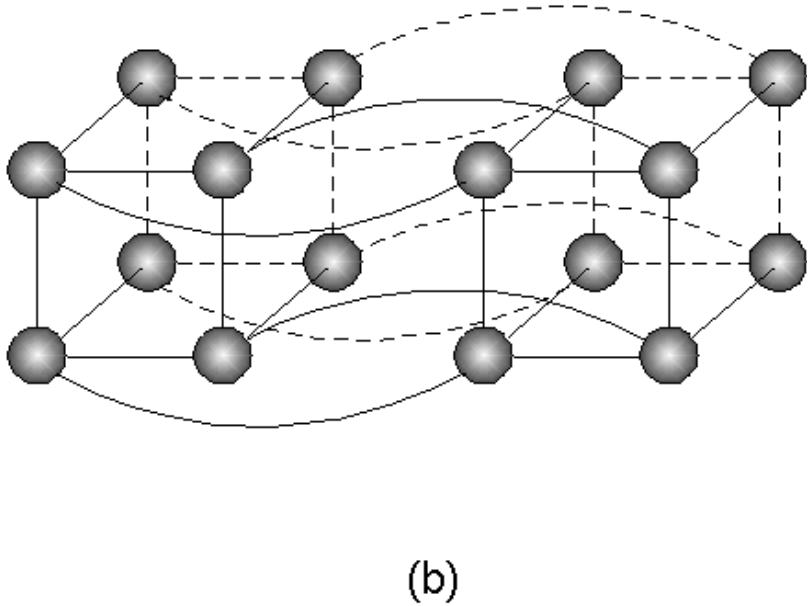


1.8 a) A crossbar switch b) An omega switching network

A possible bottleneck: the switch

Homogeneous Multicomputer Systems





1-9 a) Grid b) Hypercube

A new design aspect: locality at the network level

General Multicomputer Systems

- Hardware: see Ch1 (internet etc.)
- Loosely connected systems
  - nodes: autonomous
  - communication: slow and vulnerable
  - => cooperation at ”service level”
- Application architectures
  - multiprocessor systems: parallel computation
  - multicomputer systems: distributed systems
  - (how are parallel, concurrent, and distributed systems different?)

Software Concepts

System	Description	Main Goal
DOS	Tightly-coupled operating system for multiprocessors and homogeneous multicomputers	Hide and manage hardware resources
NOS	Loosely-coupled operating system for heterogeneous multicomputers (LAN and WAN)	Offer local services to remote clients
Middle-ware	Additional layer atop of NOS implementing general-purpose services	Provide distribution transparency

DOS: Distributed OS; NOS: Network OS

History of distributed systems

- RPC by Birel &Nelson -84
- network operating systems, distributed operating systems, distributed computing environments in mid-1990; middleware referred to relational databases
- Distributed operating systems – ”single computer”
  - Distributed process management
    - process lifecycle, inter-process communication, RPC, messaging
  - Distributed resource management
    - resource reservation and locking, deadlock detection
  - Distributed services
    - distributed file systems, distributed memory, hierarchical global naming

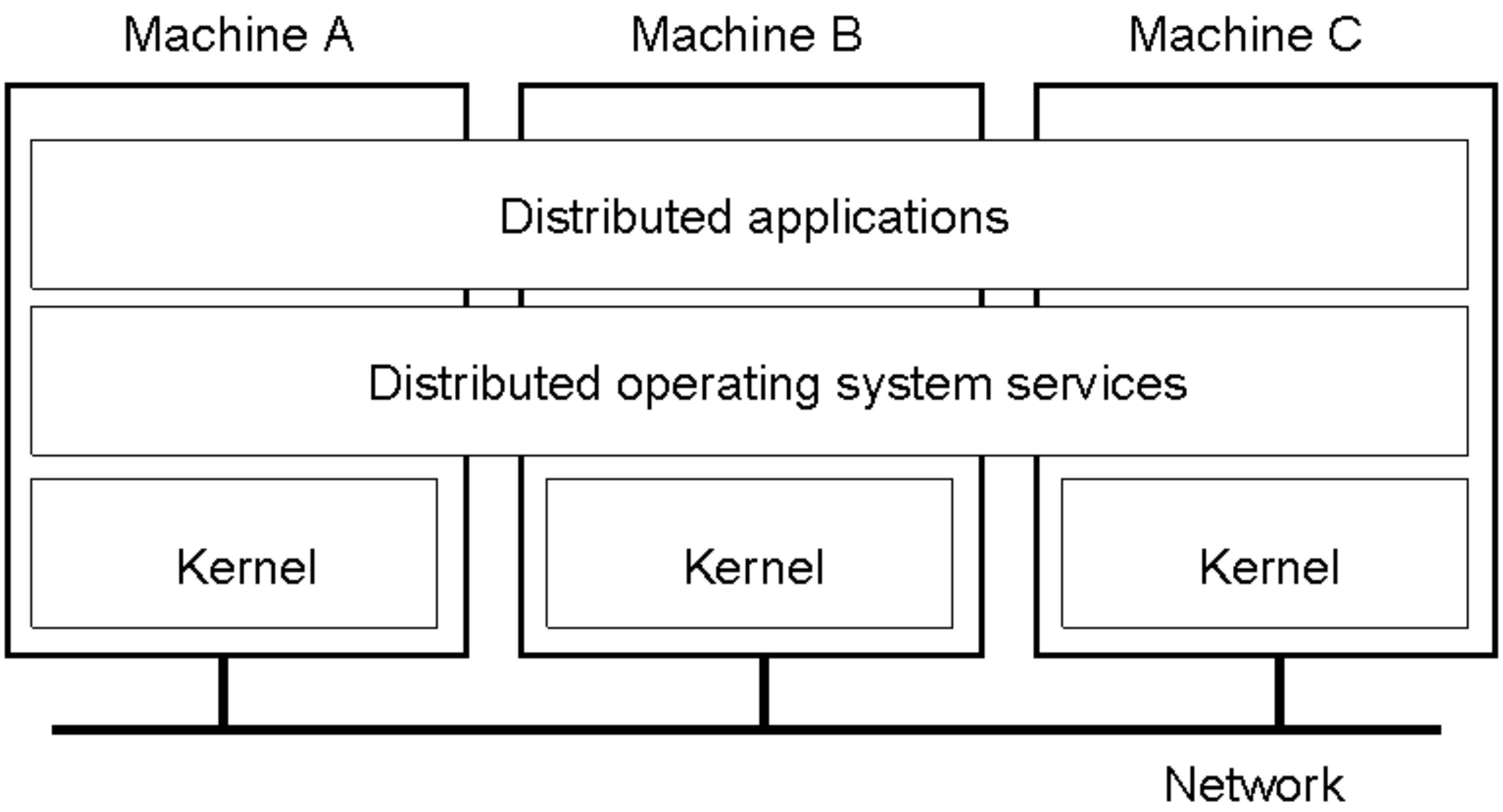
History of distributed systems

- late 1990's distribution middleware well-known
  - generic, with distributed services
  - supports standard transport protocols and provides standard API
  - available for multiple hardware, protocol stacks, operating systems
  - e.g., DCE, COM, CORBA
- present middlewares for
  - multimedia, realtime computing, telecom
  - ecommerce, adaptive / ubiquitous systems

Misconceptions tackled

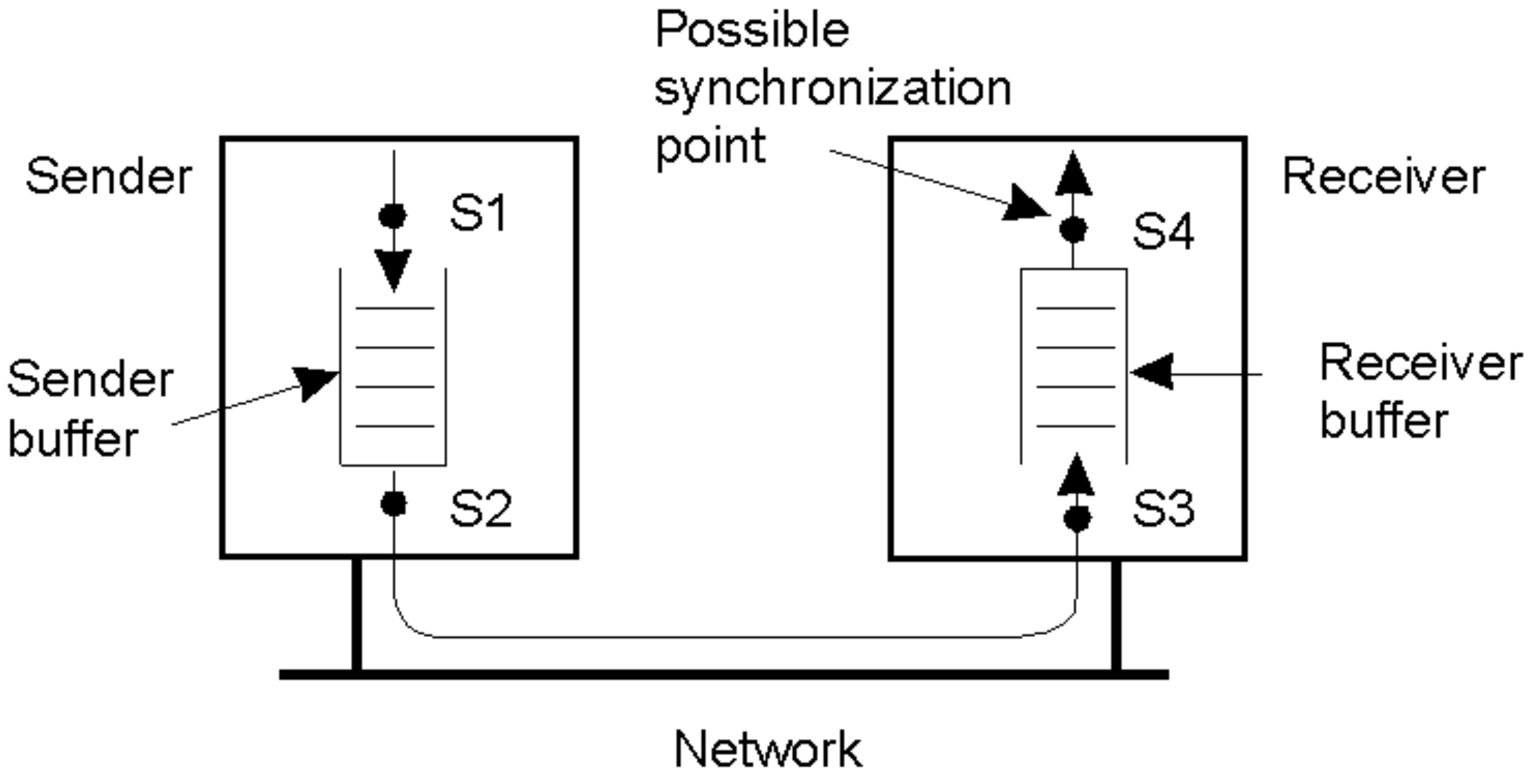
- The network is reliable
- The network is secure
- The network is homogeneous
- The topology does not change
- Latency is zero
- Bandwith is infinite
- Transport cost is zero
- There is one administrator
- There is inherent, shared knowledge

Multicomputer Operating Systems (1)



1.14 General structure of a multicomputer operating system

Multicomputer Operating Systems (2)



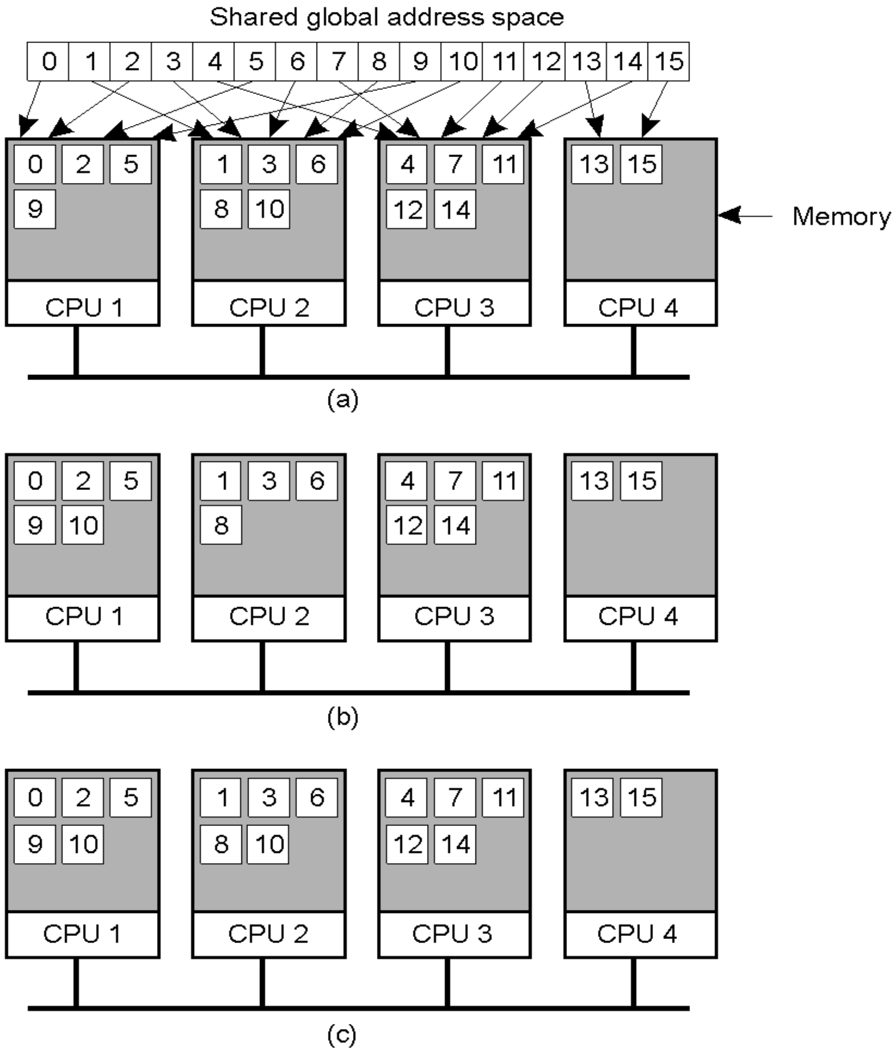
1.15 Alternatives for blocking and buffering in message passing.

Distributed Shared Memory Systems (1)

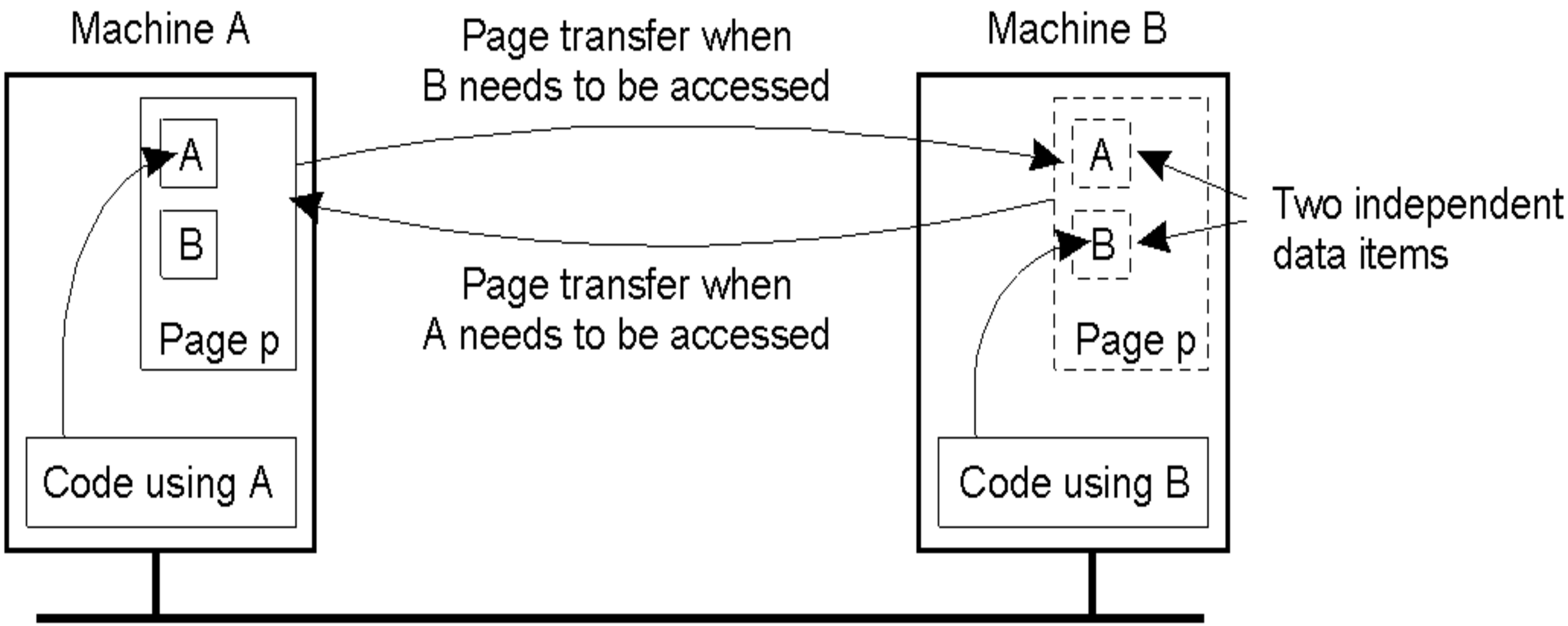
a) Pages of address space distributed among four machines

b) Situation after CPU 1 references page 10

c) Situation if page 10 is read only and replication is used

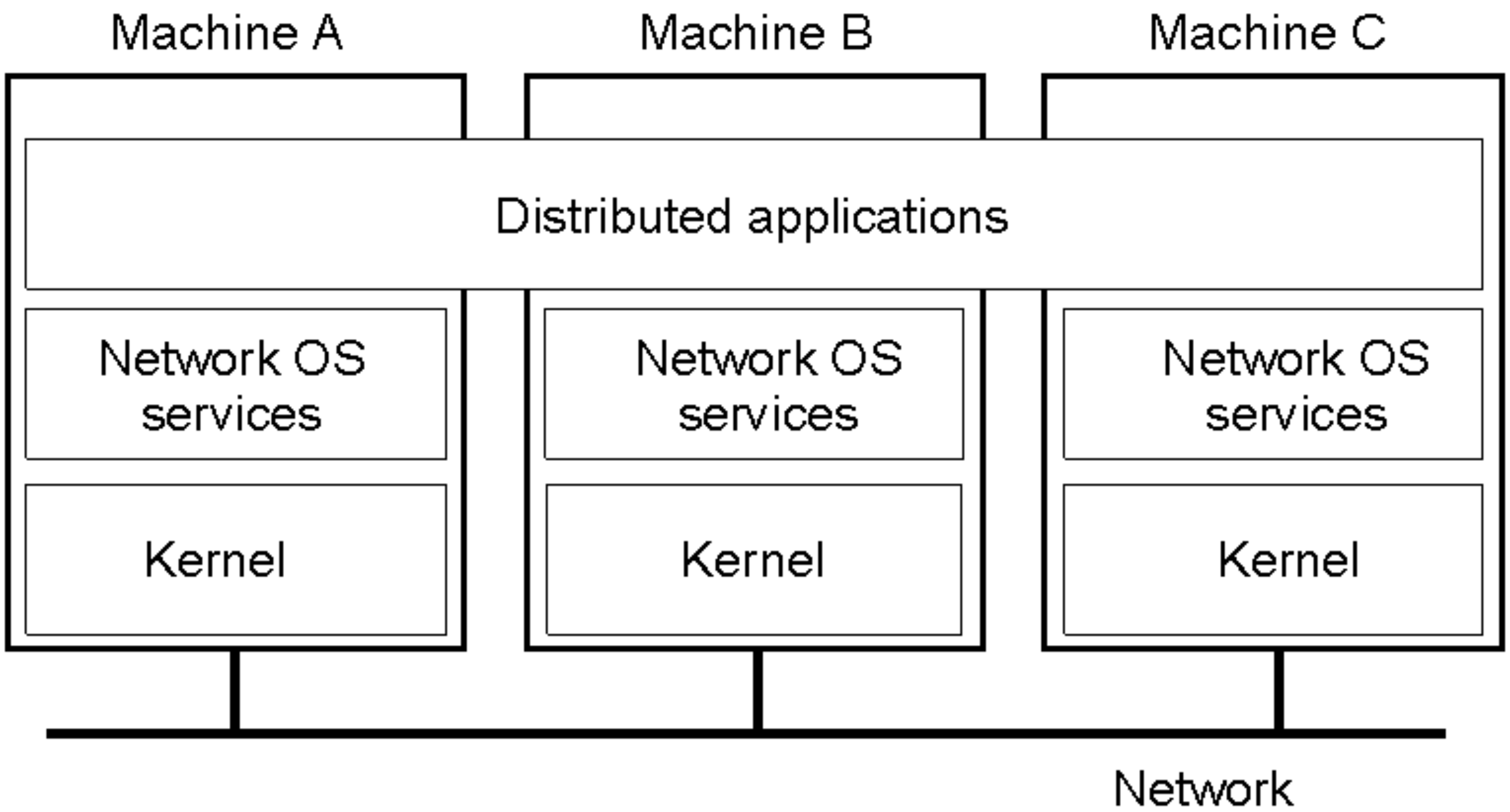


Distributed Shared Memory Systems (2)



1.18 False sharing of a page between two independent processes.

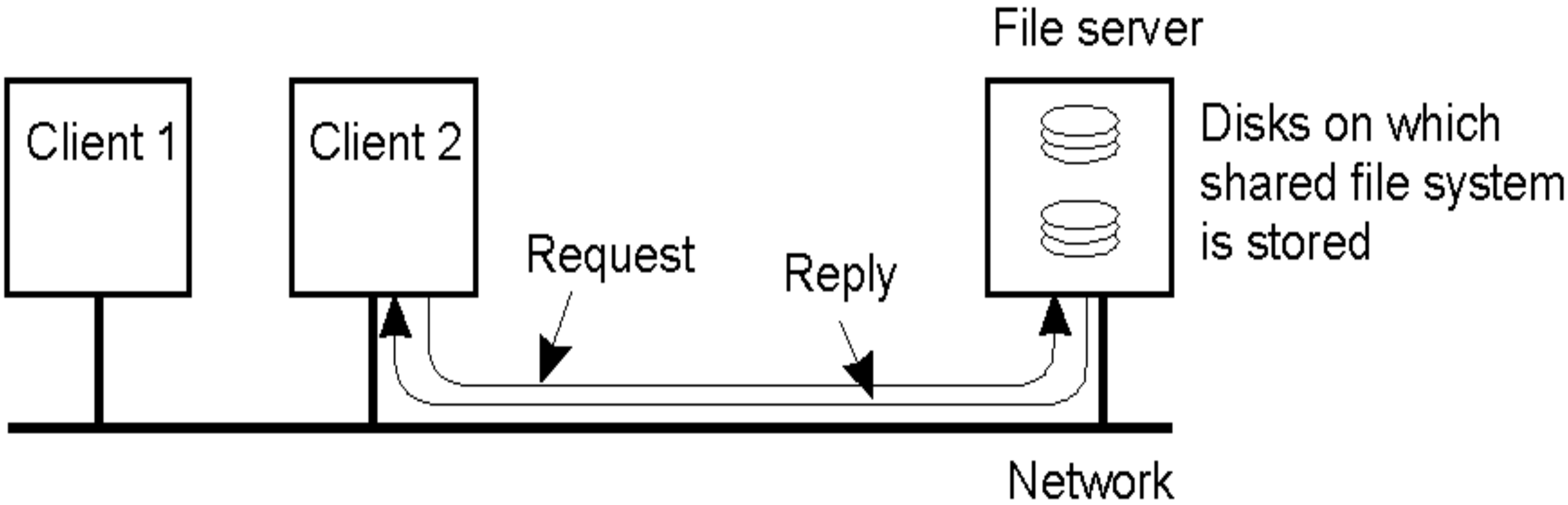
Network Operating System (1)



General structure of a network operating system.

1-19

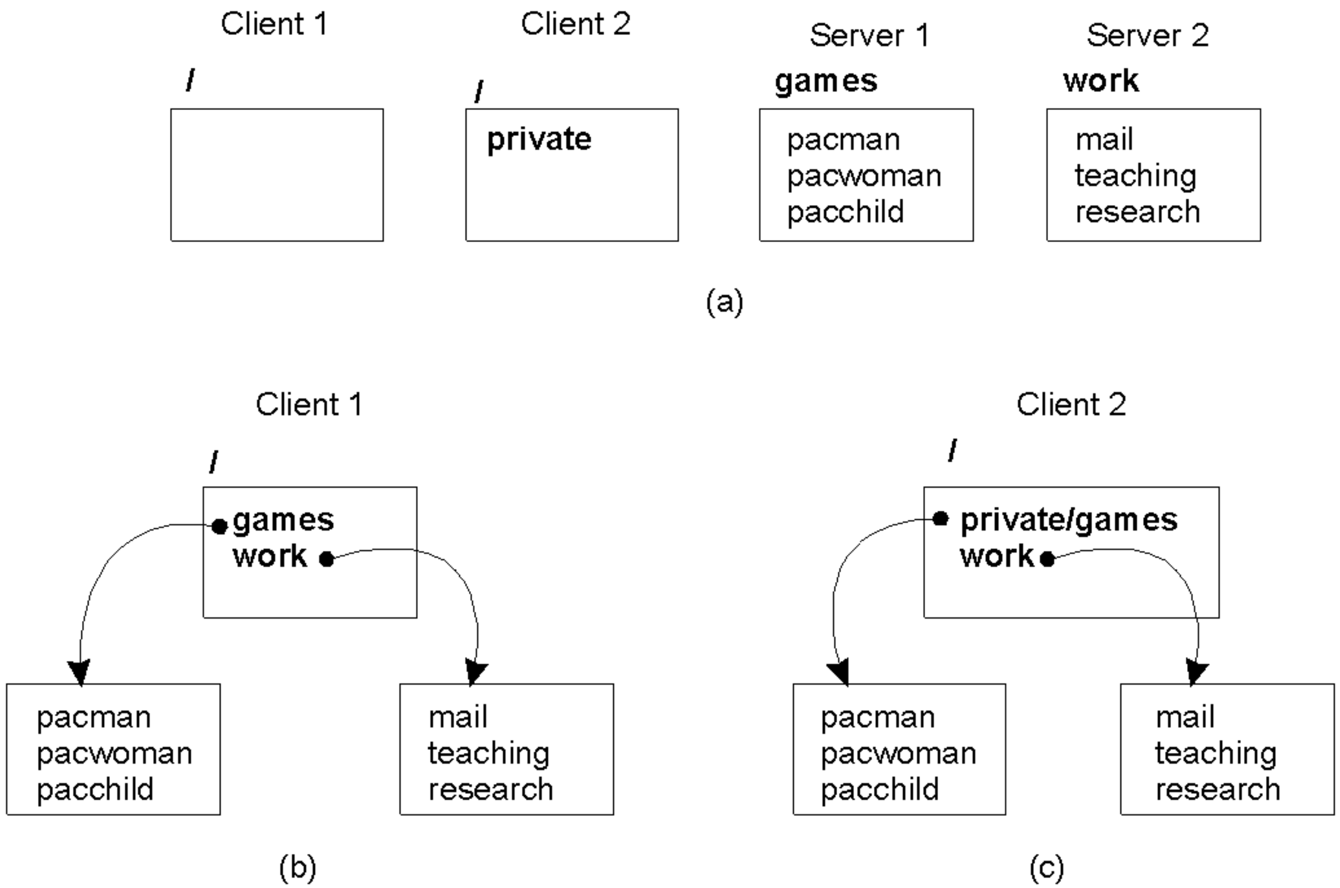
Network Operating System (2)



1-20

Two clients and a server in a network operating system.

Network Operating System (3)

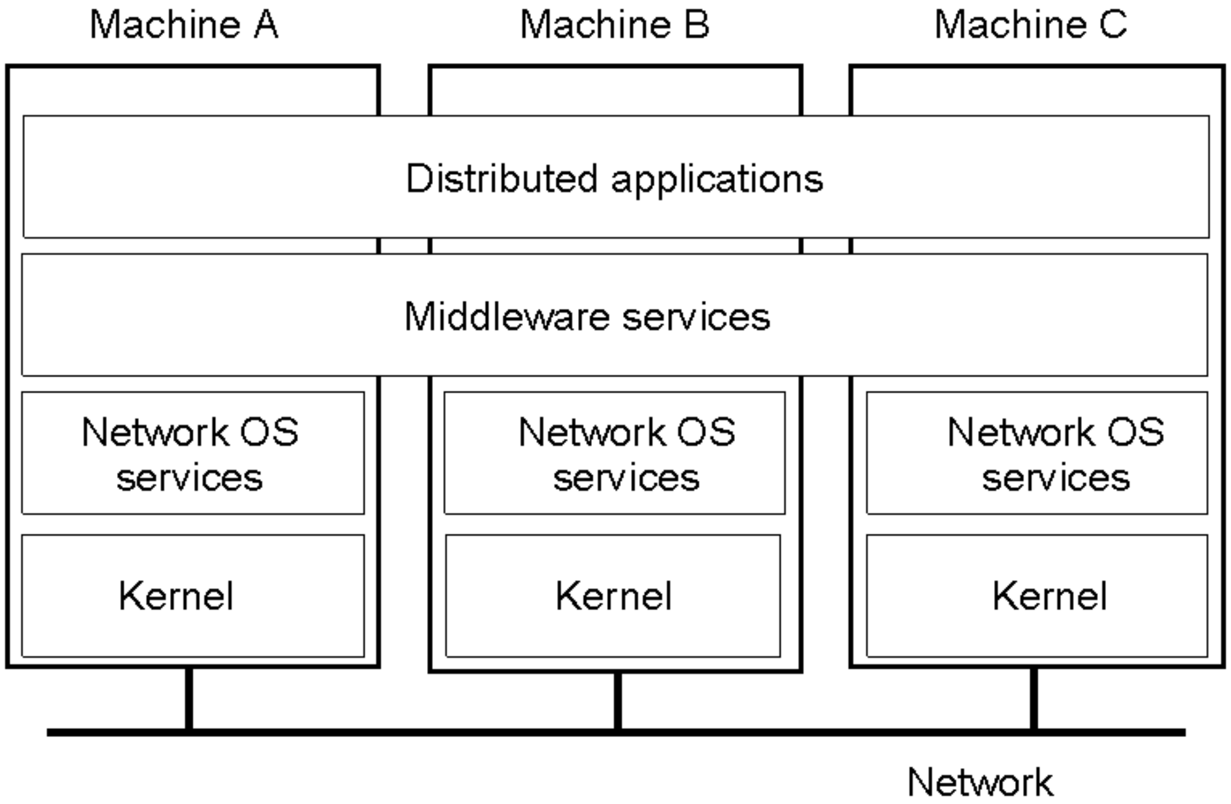


1.21 Different clients may mount the servers in different places.

Software Layers

- Platform: computer & operating system & ..
- Middleware:
  - mask heterogeneity of lower levels
  - (at least: provide a homogeneous “platform”)
  - mask separation of platform components
    - implement communication
    - implement sharing of resources
- Applications: e-mail, www-browsers, …

Positioning Middleware



1-22 General structure of a distributed system as middleware.

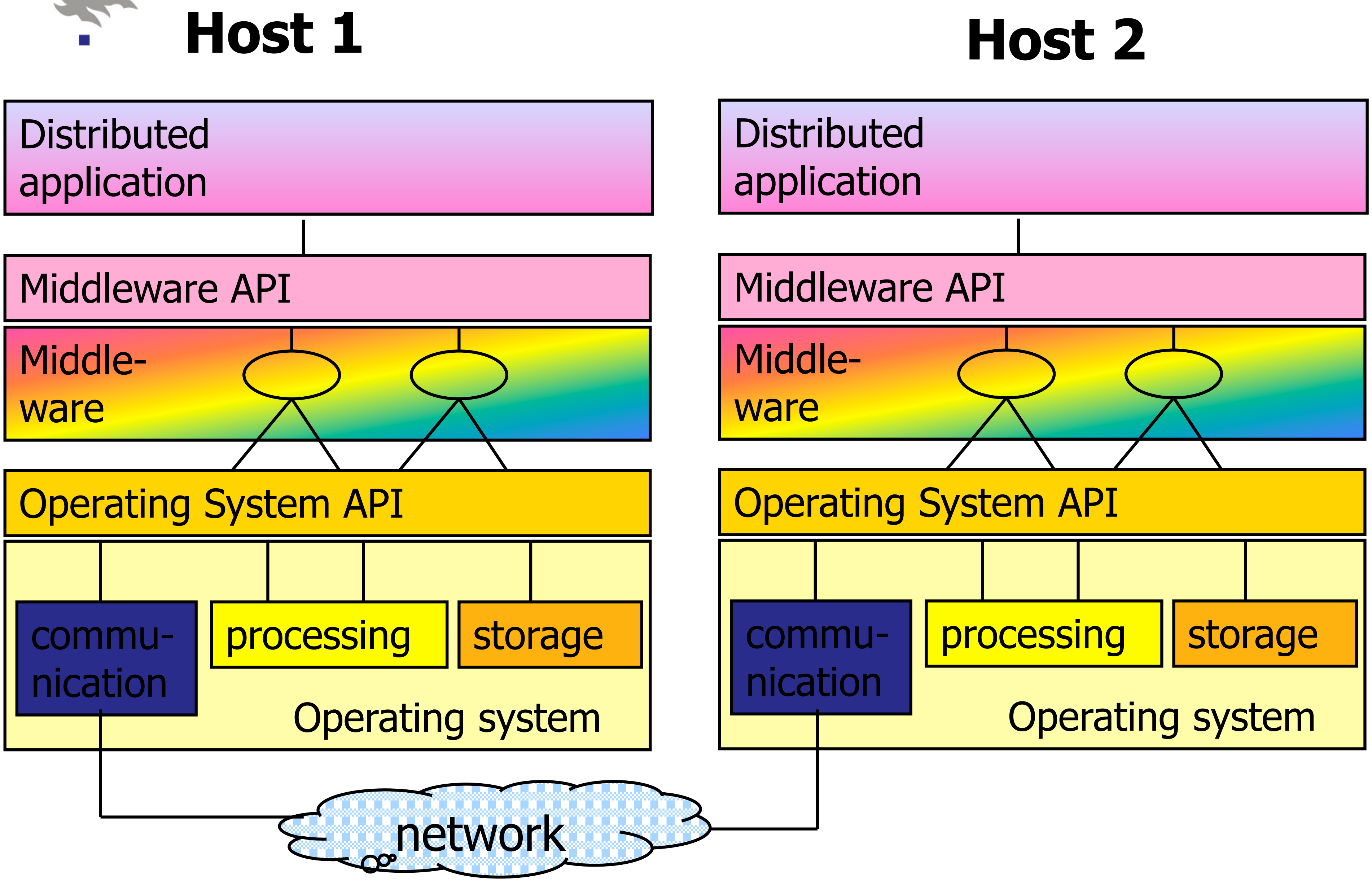
Middleware

- Operations offered by middleware
  - RMI, group communication, notification, replication, … (Sun RPC, CORBA, Java RMI, Microsoft DCOM, ...)
- Services offered by middleware
  - naming, security, transactions, persistent storage, …
- Limitations
  - ignorance of special application-level requirements

End-to-end argument:

- Communication of application-level peers at both ends is required for reliability

Middleware

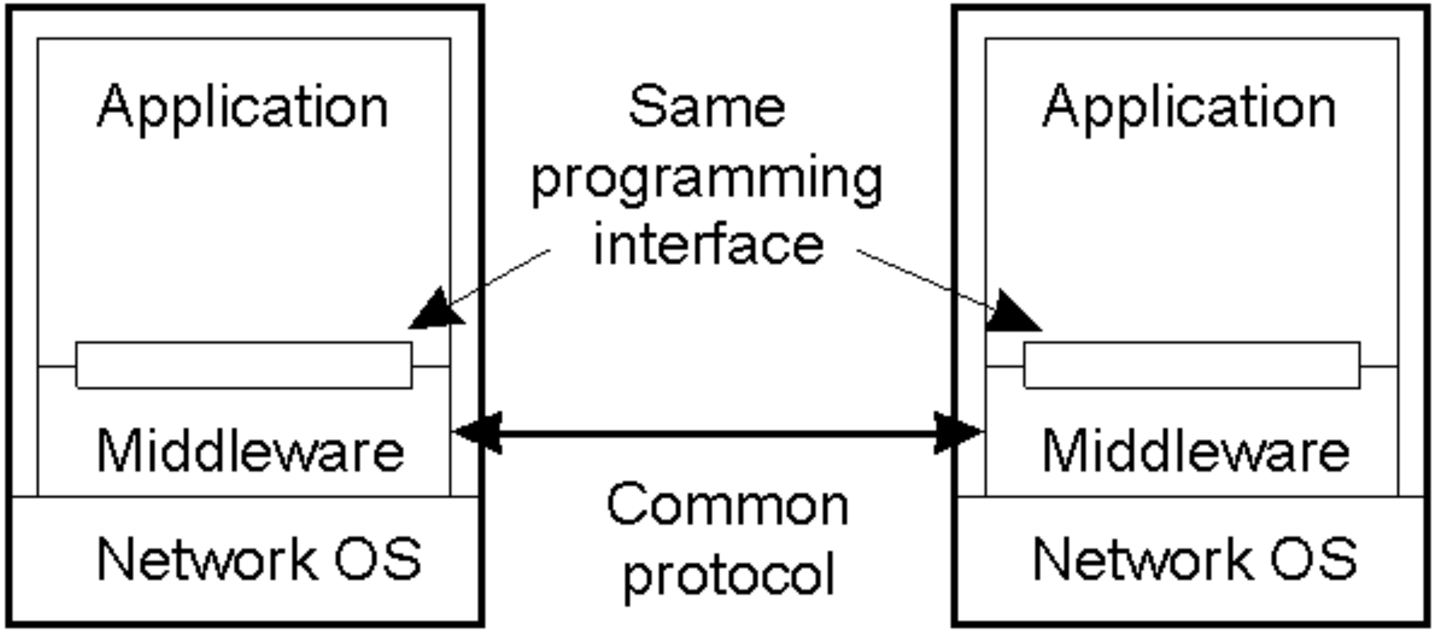

Host 1
Host 2
Distributed application
Middleware API
Middle-ware
Operating System API
commu-nication
processing
storage
Operating system
Distributed application
Middleware API
Middle-ware
Operating System API
commu-nication
processing
storage
Operating system
network

Middleware

Middleware is a class of software technologies designed to help manage the complexity and heterogeneity inherent in distributed systems. It is defined as a layer of software above the operating system but below the application program that provides a common programming abstraction across a distributed system.

Bakken 2001: Encyclopedia entry

Middleware and Openness



1.23 In an open middleware-based distributed system, the protocols used by each middleware layer should be the same, as well as the interfaces they offer to applications.

Comparison between 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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More examples on distributed software architectures

Architectural Models

- Architectural models provide a high-level view of the distribution of functionality between system components and the interaction relationships between them
- Architectural models define
  - components (logical components deployed at physical nodes)
  - communication
- Criteria
  - performance
  - reliability
  - scalability, ..

Client-Server

- Client-server model: CoDoKi, Fig. 2.2
- Service provided by multiple servers: Fig. 2.3
- Needed:
  - name service
  - trading/broker service
  - browsing service
- Proxy servers and caches, Fig. 2.4

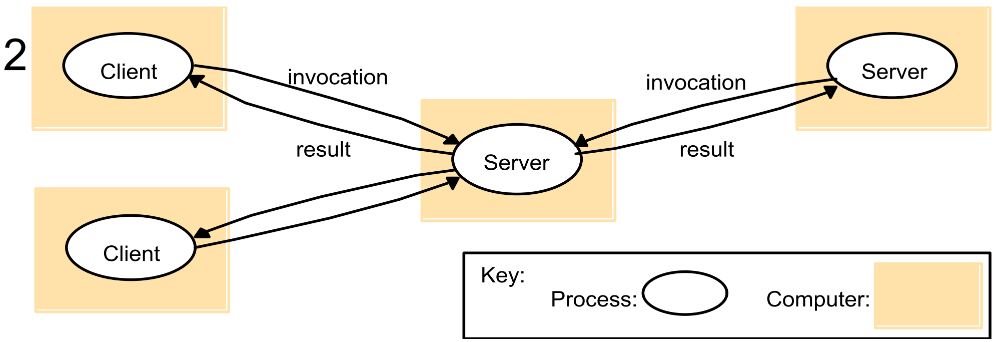
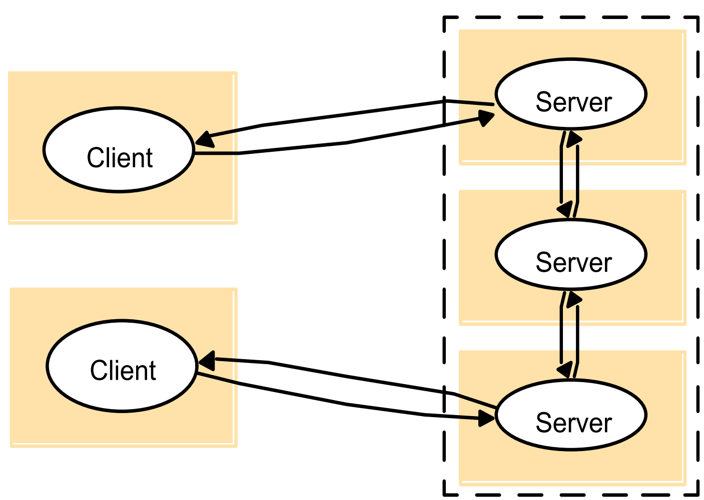


Figure 2.2 Clients invoke individual servers CoDoKi, Fig. 2.2



CoDoKi, Fig. 2.3 Figure 2.3 A service provided by multiple servers

CoDoKi, Fig. 2.4

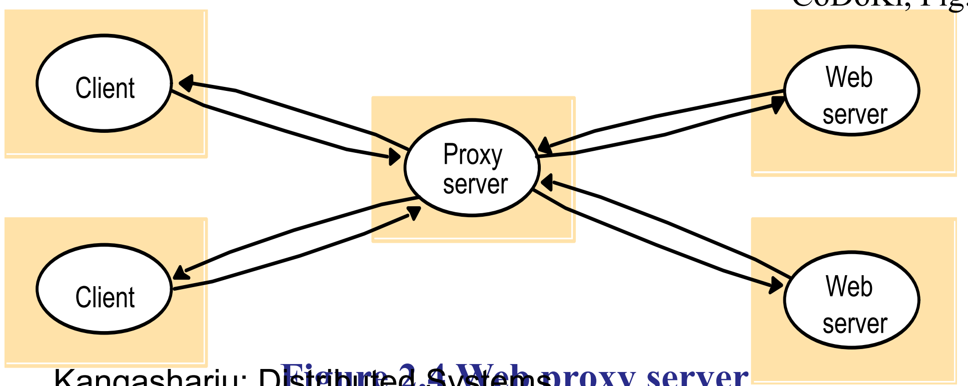


Figure 2.4 Web proxy server

An Example Client and Server (1)

```
/* Definitions needed by clients and servers.                    */
#define TRUE            1
#define MAX_PATH        255   /* maximum length of file name      */
#define BUF_SIZE        1024  /* how much data to transfer at once */
#define FILE_SERVER     243   /* file server's network address    */

/* Definitions of the allowed operations */
#define CREATE          1     /* create a new file                 */
#define READ            2     /* read data from a file and return it */
#define WRITE           3     /* write data to a file              */
#define DELETE          4     /* delete an existing file           */

/* Error codes. */
#define OK              0     /* operation performed correctly     */
#define E_BAD_OPCODE    -1    /* unknown operation requested       */
#define E_BAD_PARAM     -2    /* error in a parameter              */
#define E_IO            -3    /* disk error or other I/O error     */

/* Definition of the message format. */
struct message {
    long source;              /* sender's identity                 */
    long dest;                /* receiver's identity               */
    long opcode;              /* requested operation               */
    long count;               /* number of bytes to transfer       */
    long offset;              /* position in file to start I/O     */
    long result;              /* result of the operation           */
    char name[MAX_PATH];      /* name of file being operated on    */
    char data[BUF_SIZE];      /* data to be read or written        */
};
```

The *header.h* file used by the client and server.

An Example Client and Server (2)

```
#include <header.h>
void main(void) {
    struct message ml, m2;              /* incoming and outgoing messages    */
    int r;                              /* result code                       */

    while(TRUE) {                       /* server runs forever               */
        receive(FILE_SERVER, &ml);      /* block waiting for a message       */
        switch(ml.opcode) {             /* dispatch on type of request       */
            case CREATE:  r = do_create(&ml, &m2); break;
            case READ:    r = do_read(&ml, &m2); break;
            case WRITE:   r = do_write(&ml, &m2); break;
            case DELETE:  r = do_delete(&ml, &m2); break;
            default:      r = E_BAD_OPCODE;
        }
        m2.result = r;                  /* return result to client           */
        send(ml.source, &m2);           /* send reply                        */
    }
}
```

A sample server.

An Example Client and Server (3)

(a)

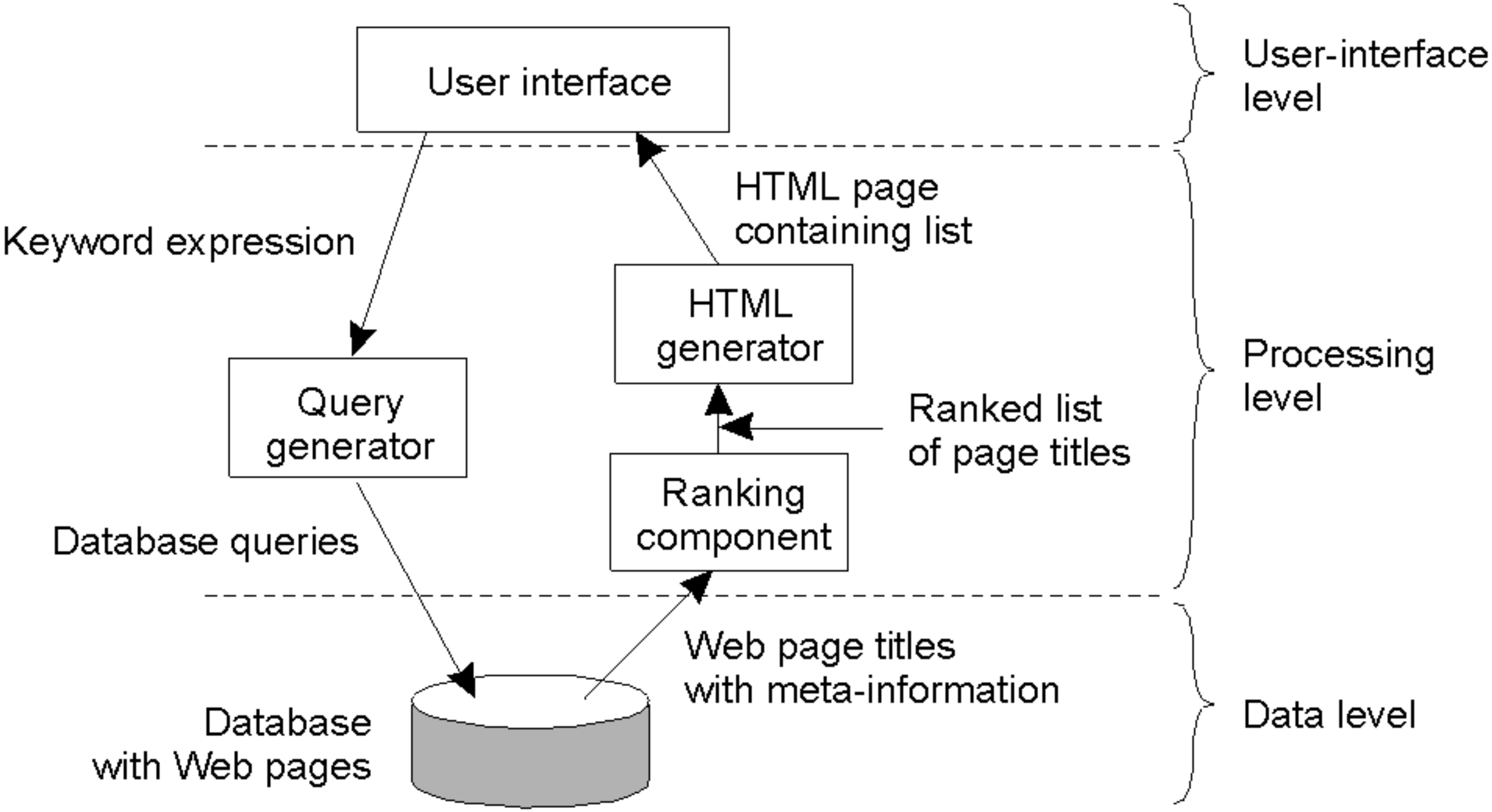
```
#include <header.h>
int copy(char *src, char *dst){                    * procedure to copy file using the server    */
     struct message ml;                            ,* message buffer                              */
     long position;                                /* current file position                       */
     long client = 110;                            /* client's address                            */

     initialize( );                                /* prepare for execution                       */
     position = 0;
     do {
          ml.opcode = READ;                        /* operation is a read                         */
          ml.offset = position;                    /* current position in the file                */
          ml.count  = BUF_SIZE;                                                                   /* how many bytes to read*/
          strcpy(&ml.name, src);                   /* copy name of file to be read to message     */
          send(FILESERVER, &ml);                   /* send the message to the file server         */
          receive(client, &ml);                    /* block waiting for the reply                 */

          /* Write the data just received to the destination file.                                */
          ml.opcode = WRITE;                       /* operation is a write                        */
          ml.offset = position;                    /* current position in the file                */
          ml.count  = ml.result;                   /* how many bytes to write                     */
          strcpy(&ml.name, dst);                   /* copy name of file to be written to buf      */
          send(FILE_SERVER, &ml);                  /* send the message to the file server         */
          receive(client, &ml);                    /* block waiting for the reply                 */
          position += ml.result;                   /* ml.result is number of bytes written        */
     } while( ml.result > 0 );                     /* iterate until done                          */
     return(ml.result >= 0 ? OK : ml result);      /* return OK or error code                     */
}
```

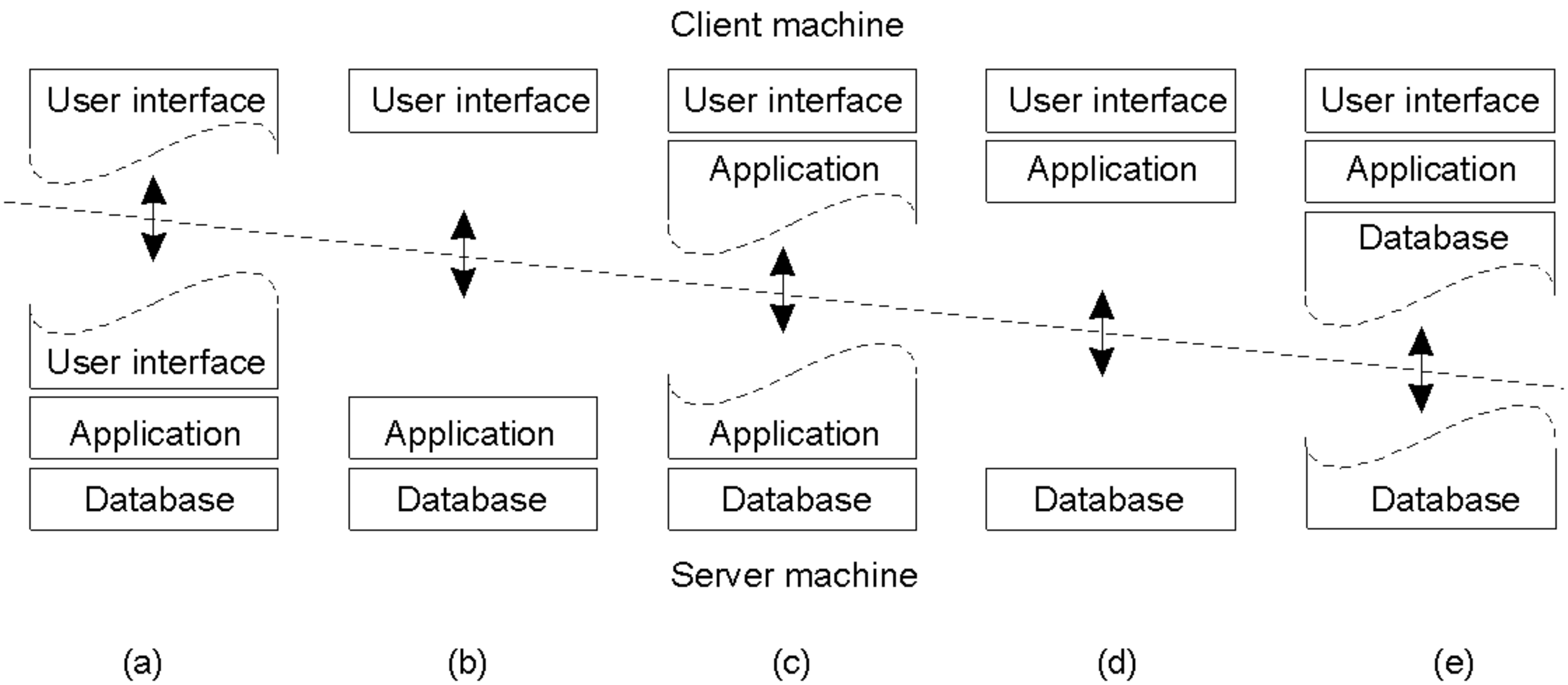
A client using the server to copy a file.

Processing Level



1-28 The general organization of an Internet search engine into three different layers

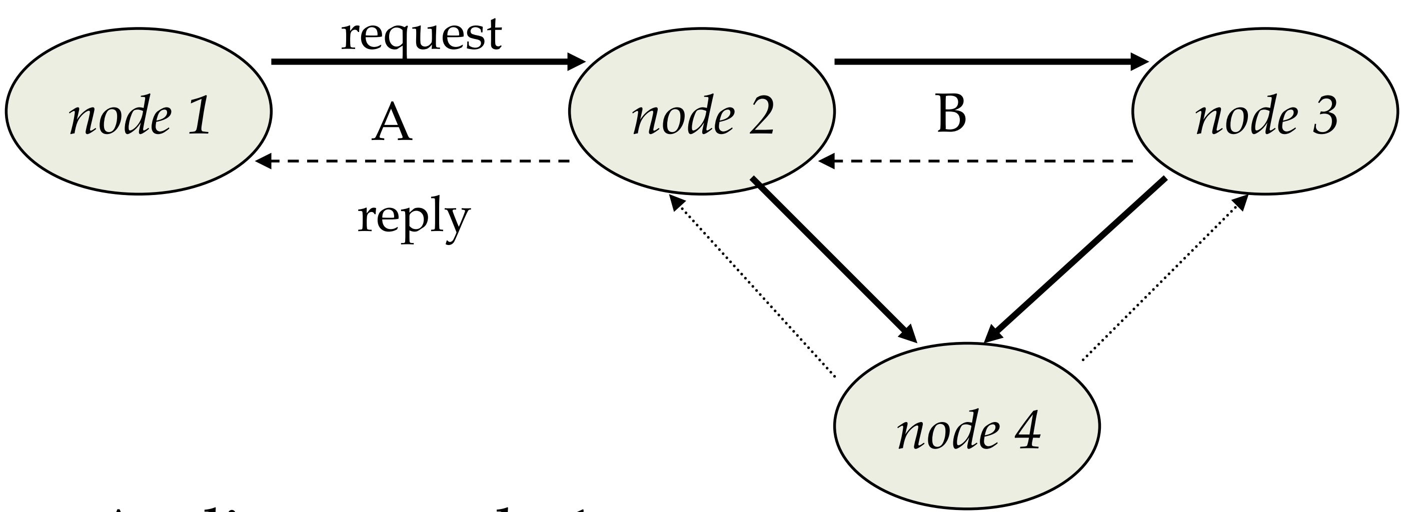
Multitiered Architectures (1)



1-29 Alternative client-server organizations.

Multitiered Architectures (2)

Client - server: generalizations

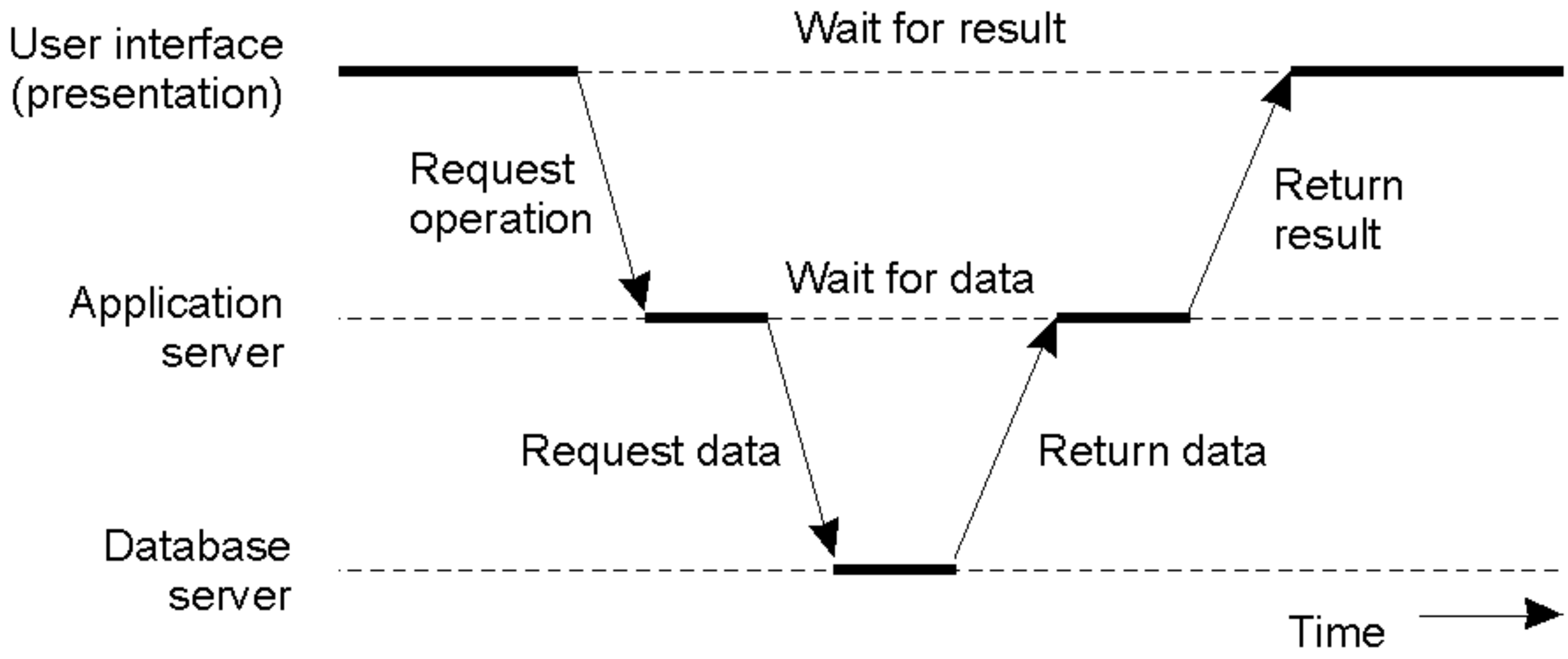


A client: node 1
server: node 2

B client: node 2
server: node 3

the concept is related to communication not to nodes

Multitiered Architectures (3)



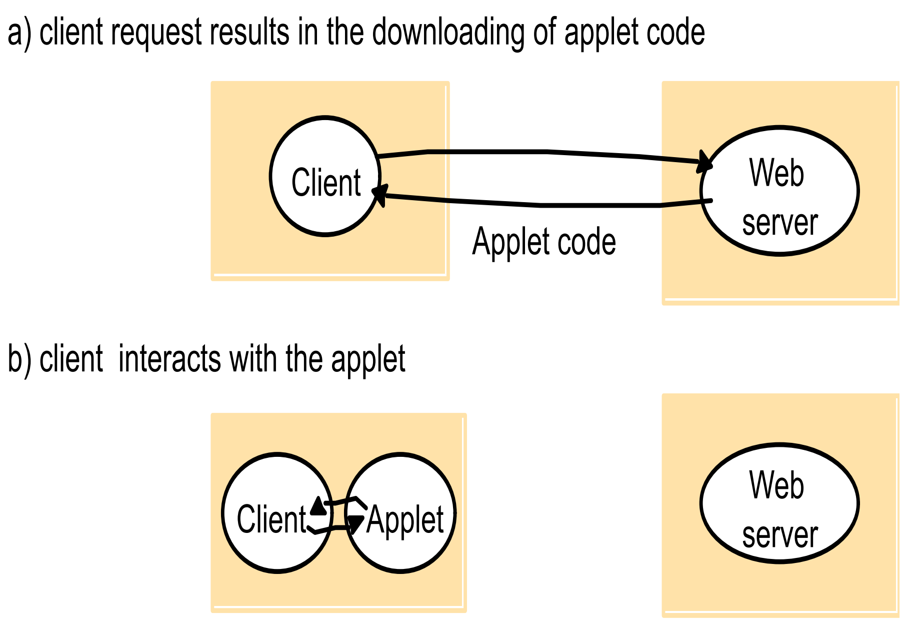
1-30 An example of a server acting as a client.

Variations on the Client-Server model

- Mobile code

  the service is provided using a procedure

  - executed by a process in the server node
  - downloaded to the client and executed locally Fig. 2.6
  - push service: the initiator is the server
- Mobile agents
  - “a running program” (code & data) travels
  - needed: an agent platform



CoDoKi, Fig. 2.6 **Figure 2.6 Web applets**

Variations on the Client-Server model (cont.)

- Network computers
  - “diskless workstations”
  - needed code and data downloaded for execution
- Thin clients
  - “PC”: user interface
  - server: execution of computations (Fig. 2.7)
  - example: Unix X-11 window system

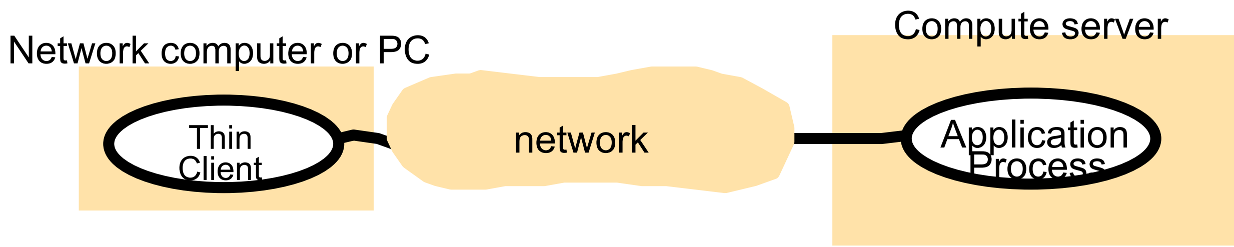


Figure 2.7 Thin clients and compute servers

CoDoKi, Fig. 2.7

Variations on the Client-Server model (cont.)

- Mobile devices and spontaneous networks, ad hoc networks (Fig. 2.8)
- Needed
  - easy connection to a local network
  - easy integration with local services
- Problems
  - limited connectivity
  - security and privacy
- Discovery service
  two interfaces:
  registration, lookup

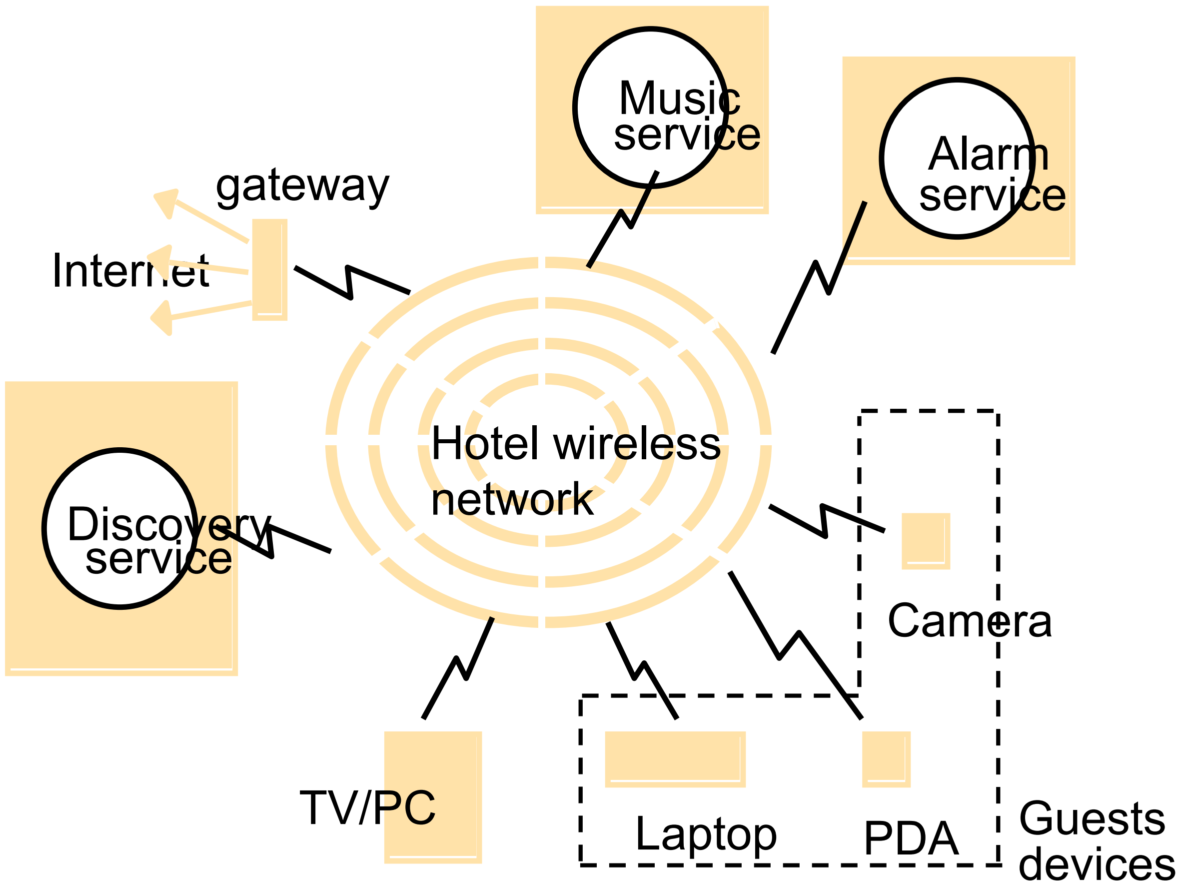
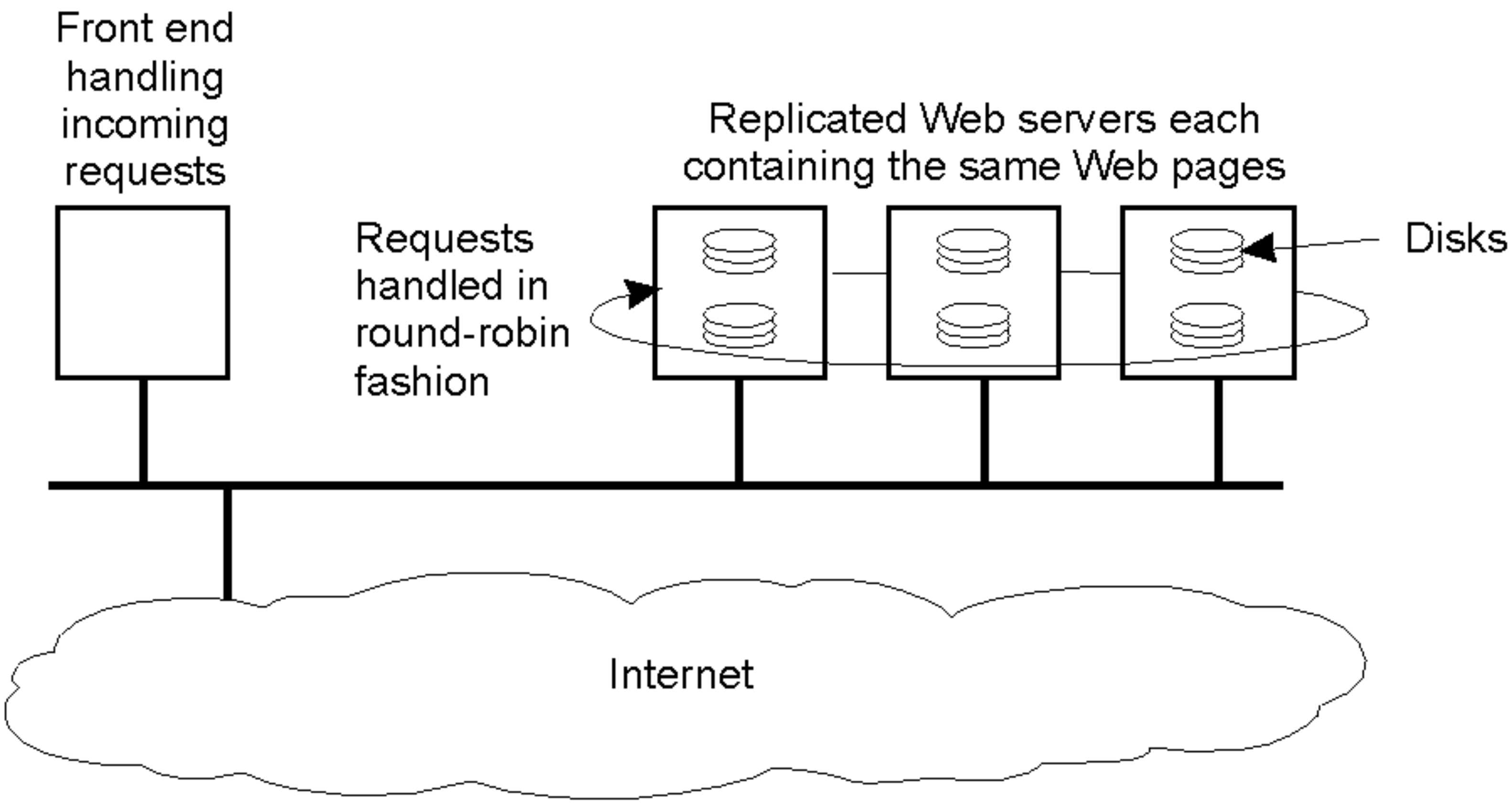


Figure 2.8 Spontaneous networking in a hotel

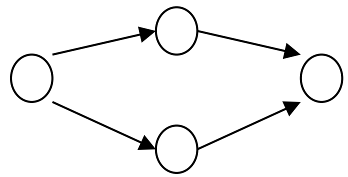
Modern Architectures



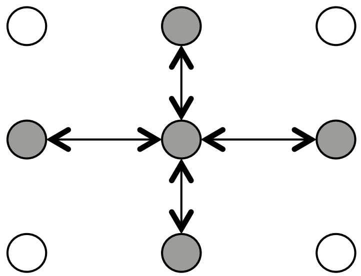
1-31 An example of horizontal distribution of a Web service.

Other Architectures

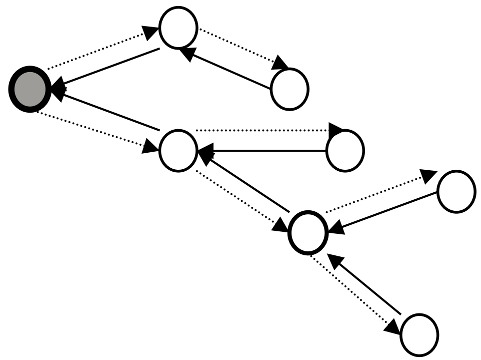
- Andrews paradigms:
  filter: a generalization of producers and consumers



heartbeat



probe echo



- Peer to peer

CoDoKi, Fig. 2.5