

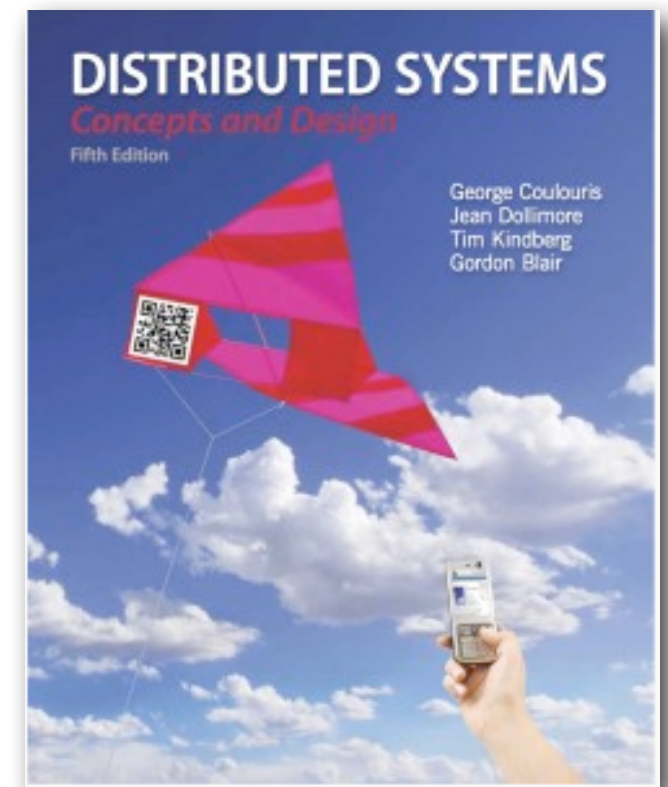
Distributed Systems: Models and Design

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DTU Compute

-
1. Architectural Models
 2. Interaction Model
 3. Design Challenges
 4. Case Study: Design of a Client-Server System



Architectural vs Fundamental Models

- Systems that are intended for use in real-world environments should be designed to function correctly in the widest possible range of circumstances and in the face of many possible difficulties and threats
- An **architectural model** is concerned with the **placement** of its components and the **relationships between them**
 - ▶ client-server systems
 - ▶ peer-to-peer systems
- **Fundamental models** are concerned with a more **abstract description** of the **properties** that are **common in all of the architectural models**

Architectural Models



- The **architecture of a system** is its structure in terms of separately specified components and their interrelationships
- 4 **fundamental building blocks** (and 4 key questions):
 1. **Communicating entities**: *what are the entities that are communicating in the distributed system?*
 2. **Communication paradigms**: *how do these entities communicate, or, more specifically, what communication paradigm is used?*
 3. **Roles and responsibilities**: *what (potentially changing) roles and responsibilities do these entities have in the overall architecture?*
 4. **Placement**: *how are these entities mapped on to the physical distributed infrastructure (i.e., what is their placement)?*

Communicating Entities

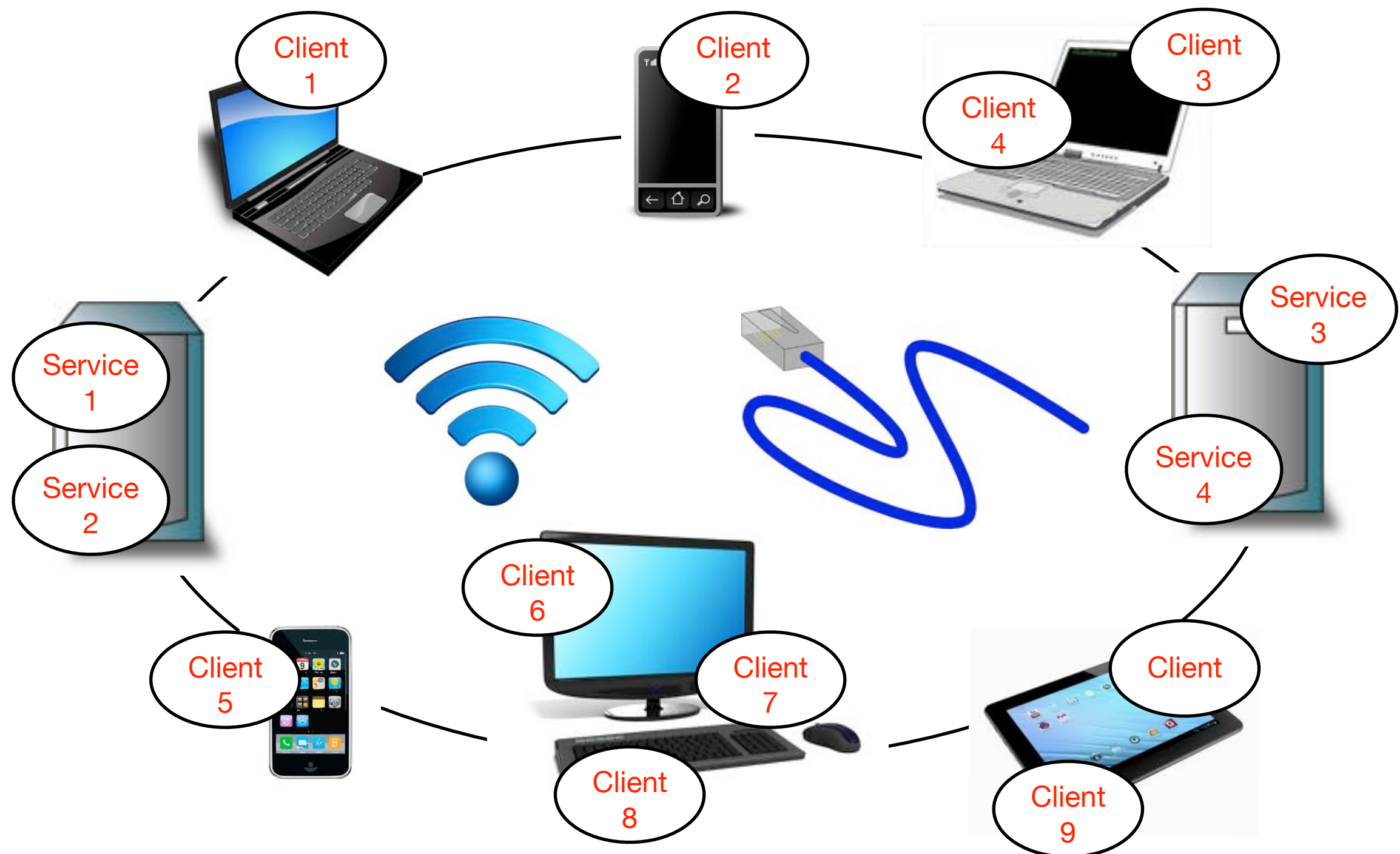
What are the entities that are communicating in the distributed system?

Communicating Entities

- **System perspective:**

- ▶ communicating entities are **processes**
- ▶ **distributed system**: **processes coupled with appropriate interprocess communication paradigms**
- ▶ two caveats:
 - in some environment, such as **sensor networks**, the underlying operating systems may not support process abstractions, and hence the entities that communicate in such systems are **nodes**
 - in most distributed environments, processes are supplemented by **threads (lightweight processes)**, so, strictly speaking, it is threads that are endpoints of communication

Processes VS Devices



Communicating Entities

- **Programming perspective:**

- ▶ more **problem-oriented abstractions** have been proposed, such as **distributed objects**, **multi-agent systems**, **Web services**, ...
- ▶ distributed objects:
 - introduced to enable and encourage the use of **object-oriented approaches in distributed systems**
 - **computation consists of a number of interacting objects** representing natural units of decomposition for the given problem domain
 - objects are **accessed via interfaces**, with an associated interface definition language providing a specification of the **methods** defined on an object

Communication Paradigms

How do entities communicate in a distributed systems?

(What communication paradigm is used?)

Communication Paradigms

- 3 types of **communication paradigm** (cont.):
 - ▶ **interprocess communication**
low level support for communication between processes in the distributed system, including message-passing primitives, socket programming, multicast communication
 - ▶ **remote invocation**
most common communication paradigm, based on a two-way exchange between communicating entities and resulting in the calling of a remote operation (procedure or method)

Communication Paradigms

- 3 types of **communication paradigm** (cont.):
 - ▶ **indirect communication**
communication is indirect, through a third entity, allowing a **strong degree of decoupling between senders and receivers**, in particular:
 - **space uncoupling**: senders do not need to know who they are sending to
 - **time uncoupling**: senders and receivers do not need to exist at the same time

Key techniques include: group communication, publish subscribe systems, message queues, tuple spaces, distributed shared memory (DSM)

Communicating Entities and Communication Paradigms

<i>Communicating entities (what is communicating)</i>		<i>Communication paradigms (how they communicate)</i>		
<i>System-oriented entities</i>	<i>Problem- oriented entities</i>	<i>Interprocess communication</i>	<i>Remote invocation</i>	<i>Indirect communication</i>
Nodes	Objects	Message passing	Request- reply	Group communication
Processes	Components	Sockets	RPC	Publish-subscribe
	Web services	Multicast	RMI	Message queues
				Tuple spaces
				DSM

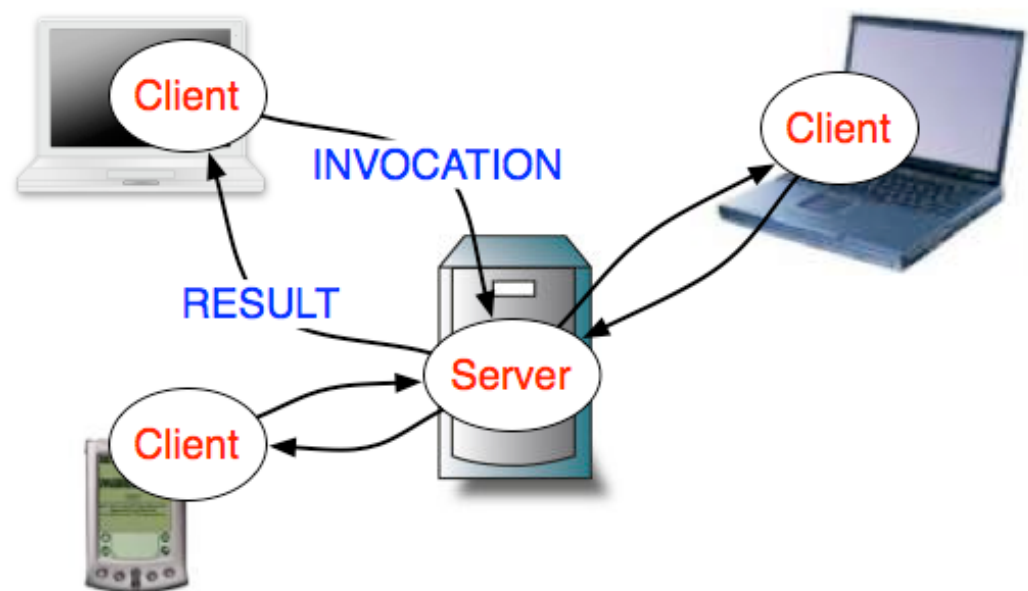
Roles & Responsibilities

What (potentially changing) roles and responsibilities do these entities have in the overall architecture?

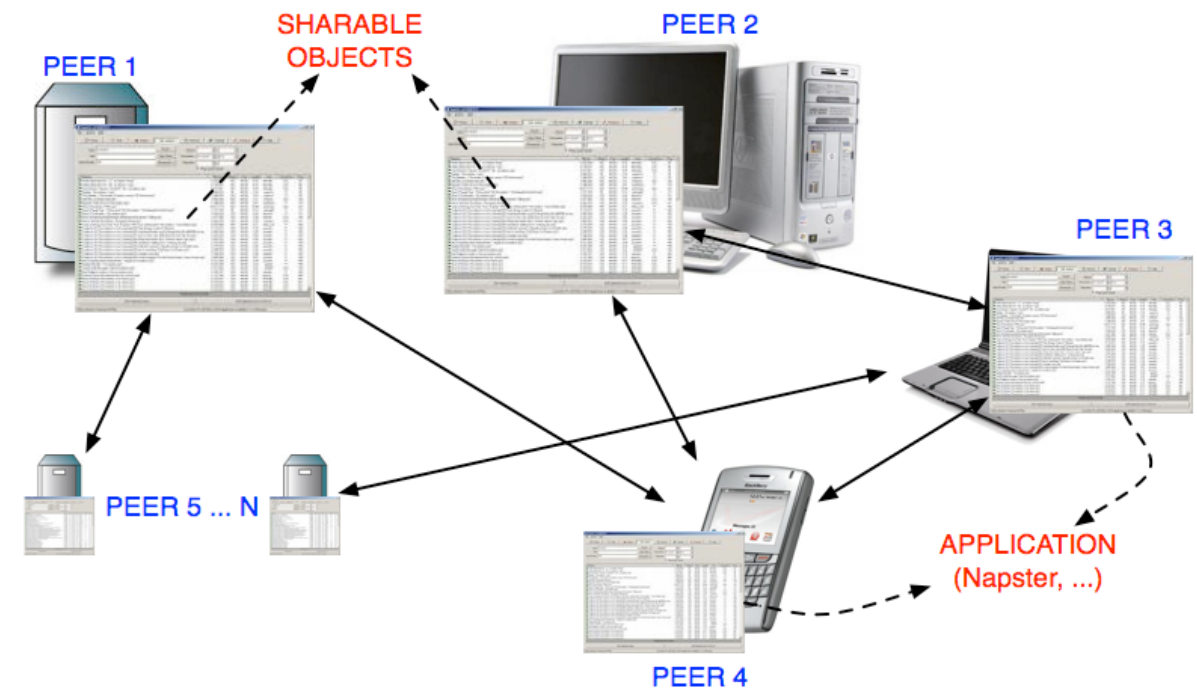
Roles & Responsibilities

- 2 architectural styles stemming from the role of individual processes

client-server

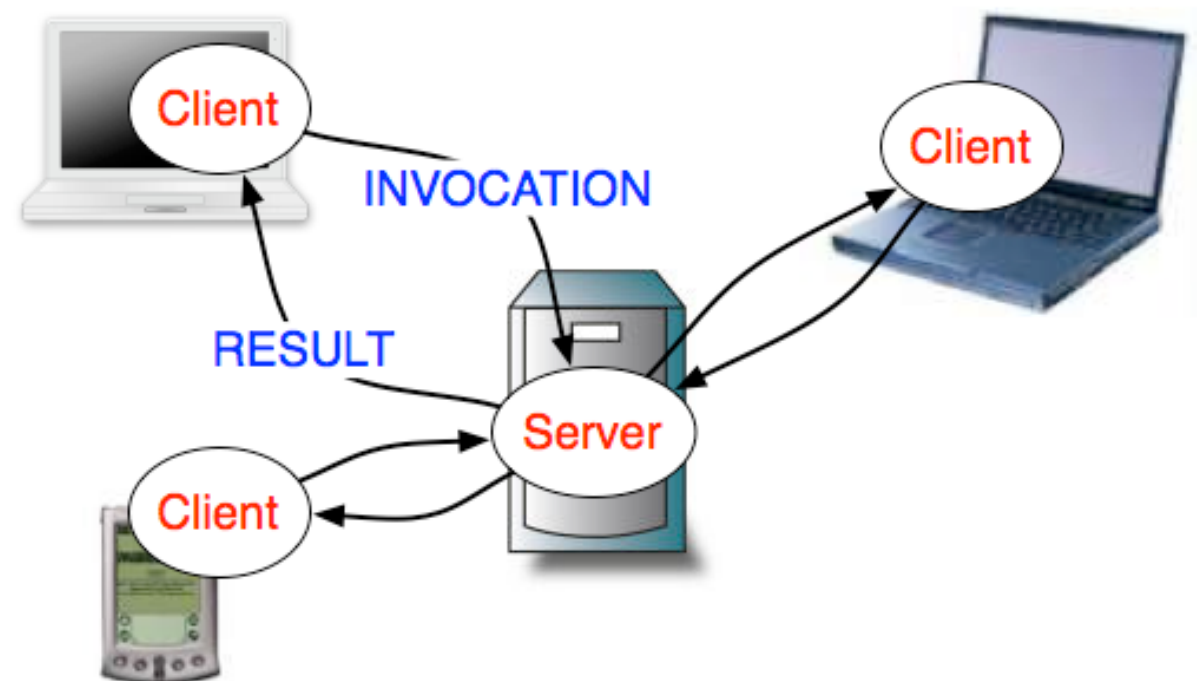
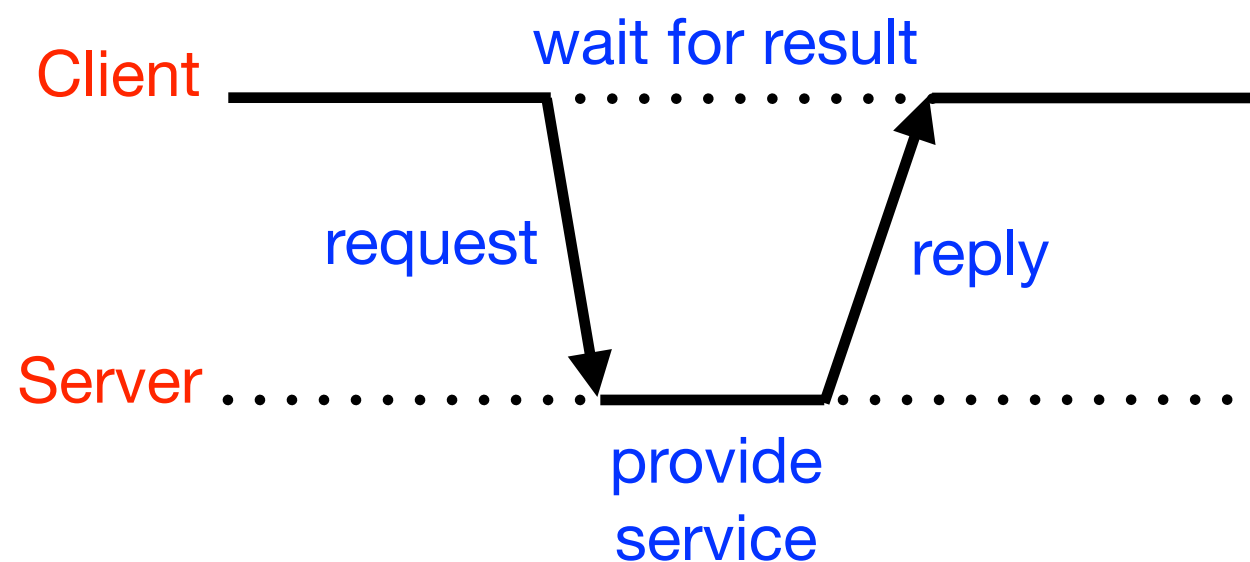


peer-to-peer (P2P)



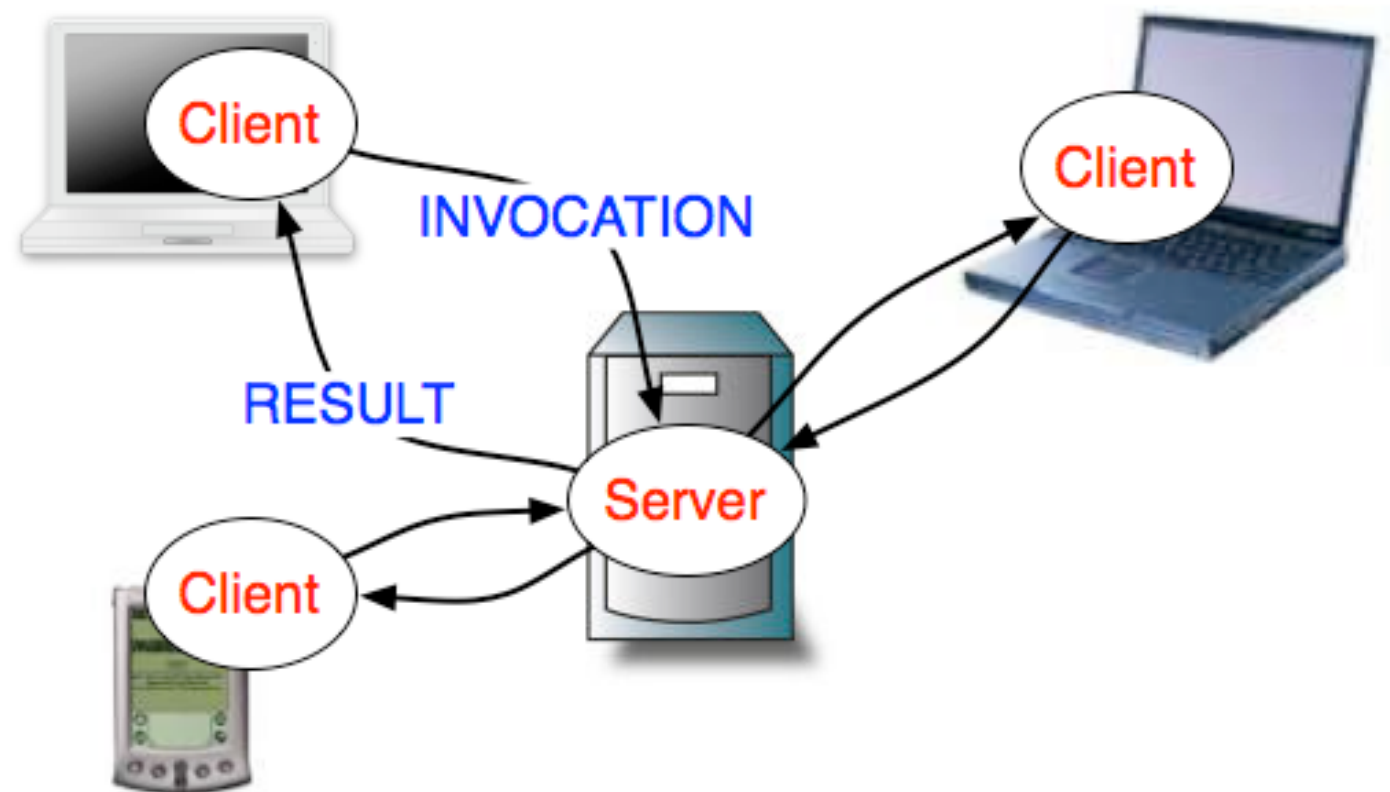
Client-Server Architectural Style

- **Processes** divided into two (possibly overlapping) groups:
 - ▶ **Server**: process implementing a specific service (file system service, database service, ...)
 - ▶ **Client**: process that requests a service from a server by sending it a request and subsequently waiting for the server's reply
- **Request-reply** protocol



Client-Server Interaction

- **Requests** are sent in messages **from clients to a server**
 - ▶ When a client sends a request for an operation to be carried out, we say that the client **invokes an operation upon the server**
- **Replies** are sent in messages **from the server to the clients**
- **Remote invocation**: a **complete interaction between a client and a server** (from the point when the client sends its request to when it receives the server's response)



Example: The Web as Client-Server Resource Sharing System

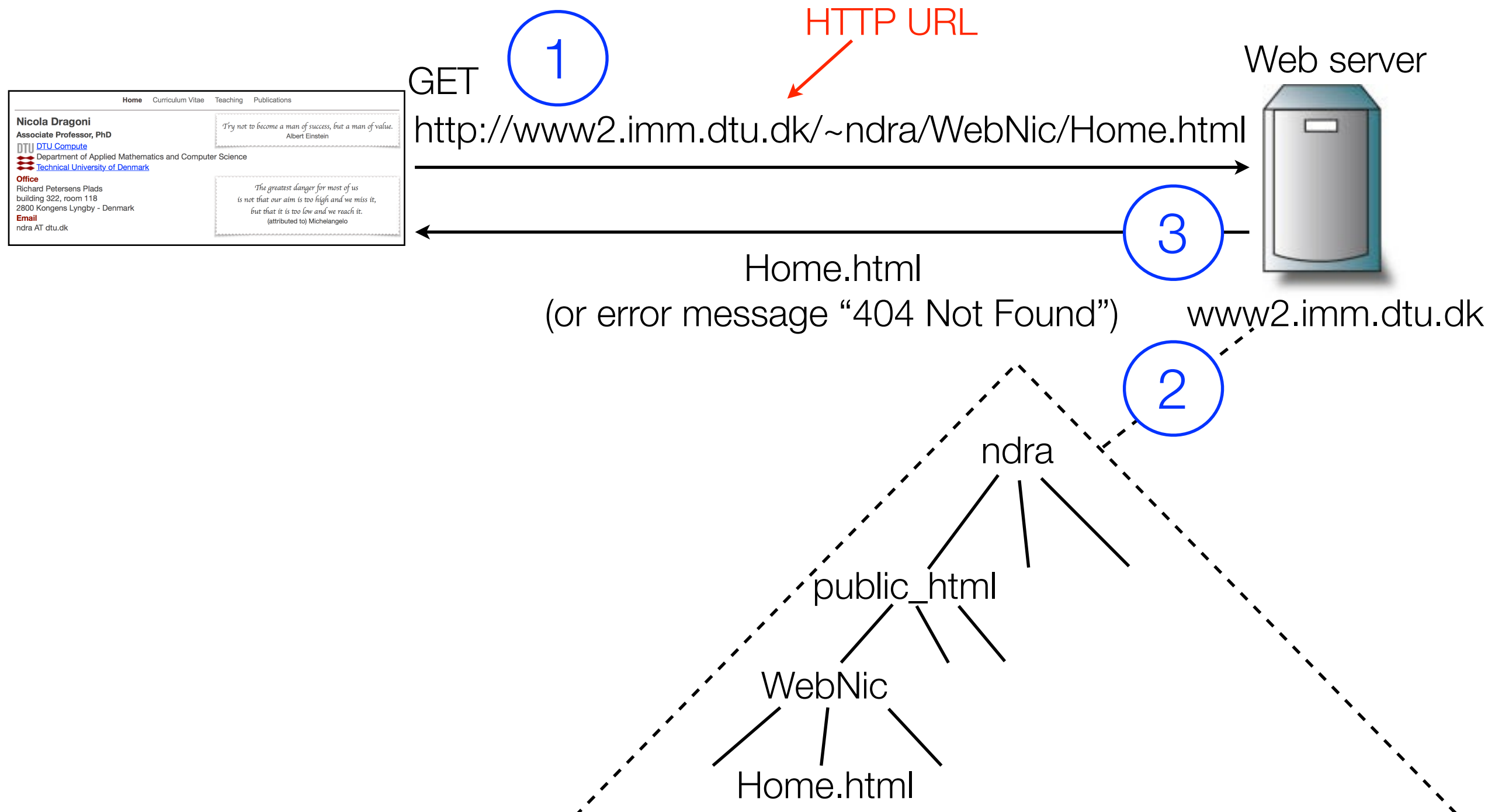
- The **World Wide Web** is an evolving and open system for publishing and accessing resources and services across the Internet
- For instance, through **Web browsers** (clients) users can
 - ▶ retrieve and view documents of many types
 - ▶ listen to audio streams
 - ▶ view video streams
 - ▶ and in general interact with an unlimited set of services



[Web] Main Technological Components

1. The **HyperText Markup Language (HTML)** is a language for specifying the contents and layout of pages as they are displayed by Web browsers
2. **Uniform Resource Locators (URLs)** which identify documents and other resources stored as part of the Web
3. A **client-server system architecture**, with standard rules for interaction (the **HyperText Transfer Protocol - HTTP**) by which browsers and other clients fetch documents and other resources from Web servers

Web Browser and Web Server Example



On the Client and Server Role...

- **A process can be both a client and a server**, since servers sometimes invoke operations on other servers
- The terms “client” and “server” apply only to the roles played **in a single request**
- But in general they are **distinct concepts**:
 - ▶ **clients are active** and **server are passive (reactive)**
 - ▶ **server run continuously**, whereas clients last only as long as the applications of which they form a part

On the Client-Server Role: Examples

- Example 1: a **Web server** is often a **client** of a **local file server** that manages the files in which the web pages are stored
- Example 2: **Web servers** and most **Internet services** are **clients** of the **DNS service** (which translates Internet Domain names to network addresses)
- Example 3: **search engine**
 - ▶ **Server**: it responds to queries from browser clients
 - ▶ **Client**: it runs (in the background) programs called *web crawlers* that act as clients of other web servers



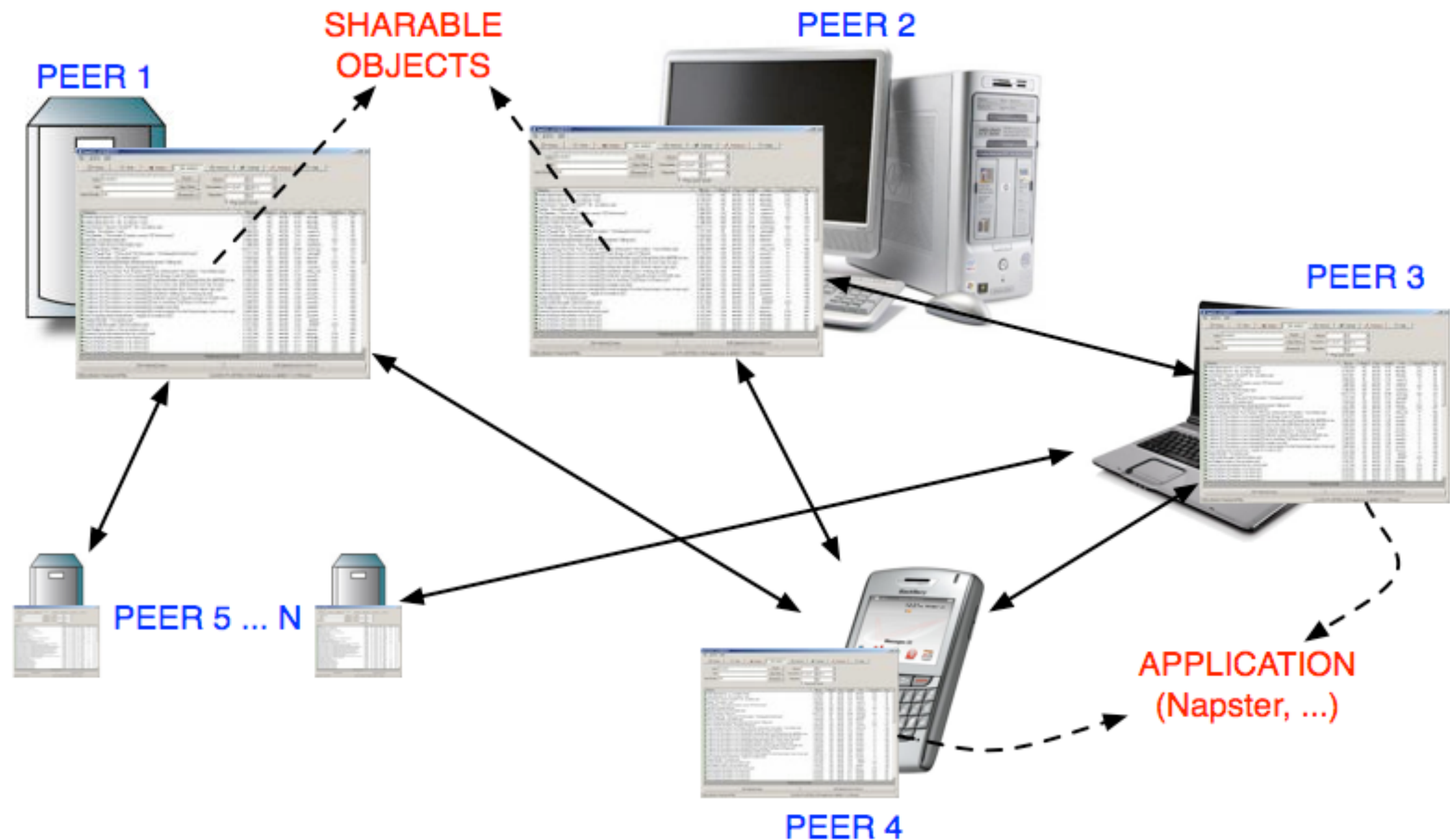
Architectural Style: Peer-to-Peer (P2P)

- All the processes involved in a task or activity play **similar roles**, interacting *cooperatively* as **peers** without **any distinction between client and server processes** or the computers that they run on
- In practical terms, **all peers run the same program** and **offer the same set of interfaces** to each other



The **aim** of the P2P architecture is **to exploit the resources (both data and hardware) in a large number of participating computers for the fulfilment of a given task or activity**

Distributed Application Based on a P2P Architecture



Placement

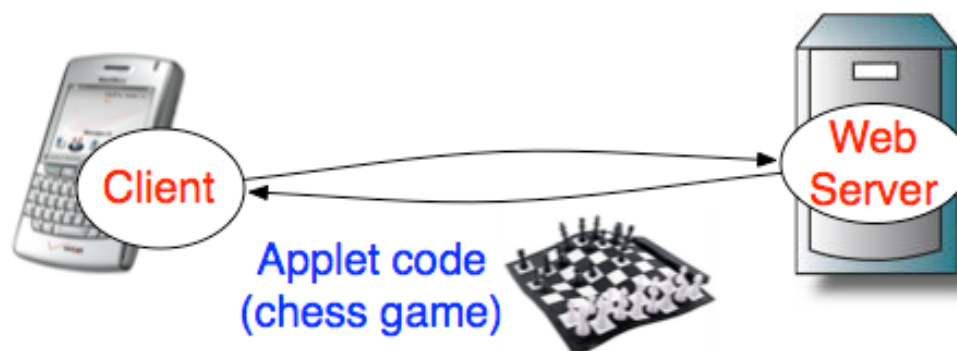
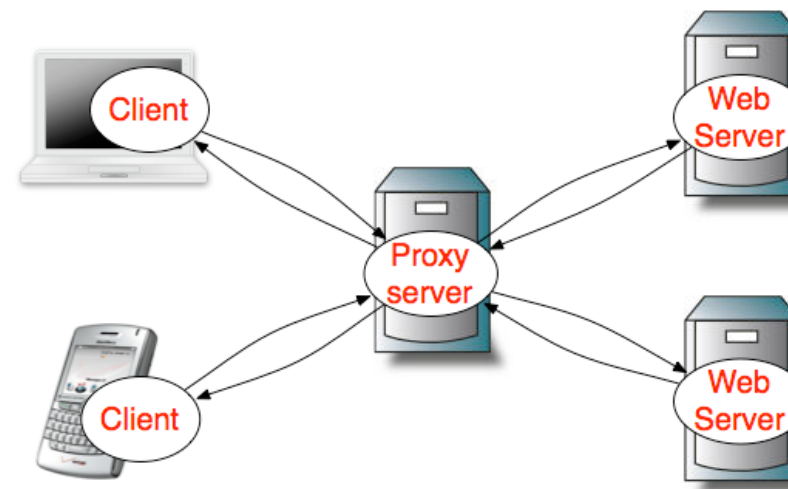
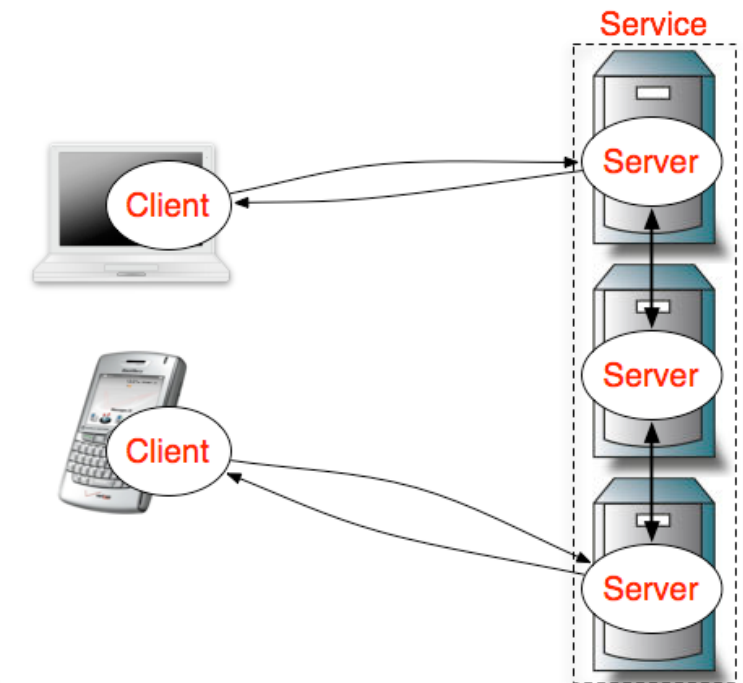
How are entities mapped on to the physical
distributed infrastructure
(i.e., what is their placement)?

Placement

- Physical distributed infrastructure usually consists of a potentially **large number of devices interconnected by a network** of arbitrary complexity
- Placement is **crucial** in terms of determining the **properties of the distributed system**, such as **performance**, **reliability** and **security**
- Placement need to take into account several aspects (machines, reliability, communication, ...) and **there are few universal guidelines to obtaining an optimal solution!**

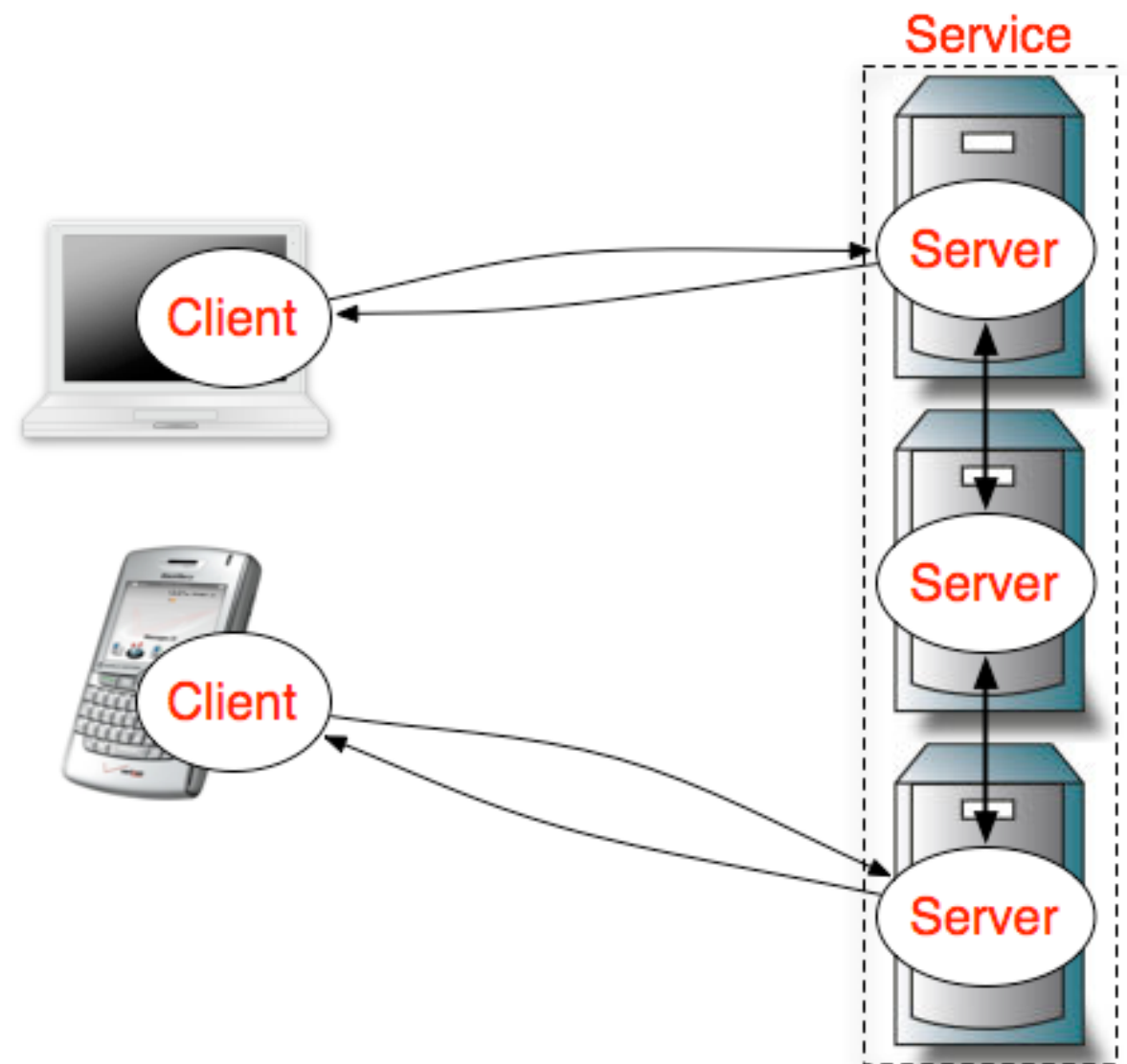
Placement Strategies

- Mapping of services to multiple servers
- Proxy server and caches
- Mobile code



Placement Strategy: Service Provided by Multiple Servers

- Services may be implemented as several server processes in separate host computers interacting as necessary to provide a service to client processes
- The servers may:
 - 1) partition the set of objects on which the service is based and distributed them between themselves (e.g. Web servers)
 - 2) they may maintain replicated copies of them on several hosts (e.g. SUN Network Information Service (NIS)).

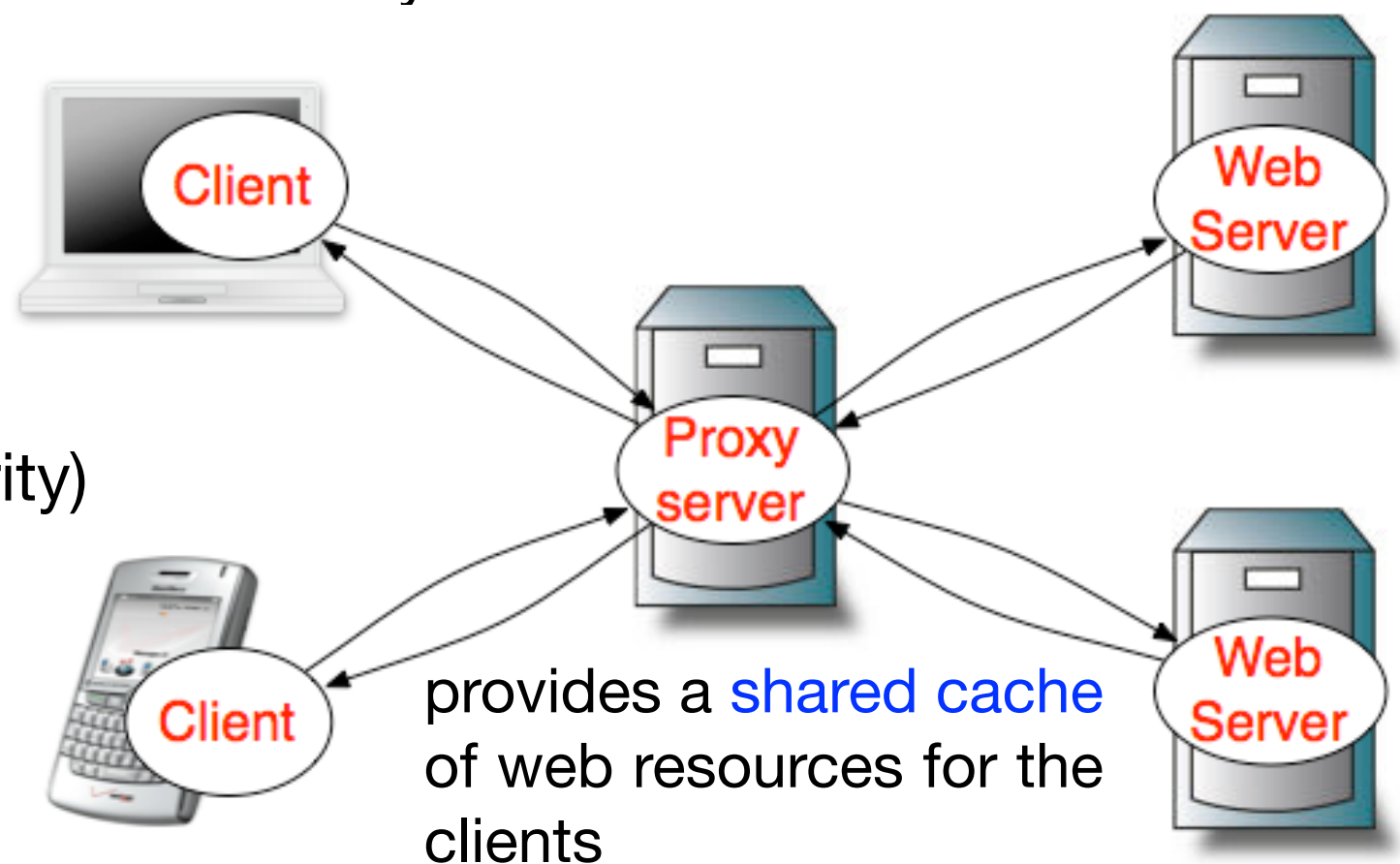


Placement Strategy: Proxy Servers and Caches

- A **cache** is a store of recently used data objects that is closer to one client or a particular set of clients than the objects themselves
- **Example 1:** Web browsers maintain a cache of recently visited pages and other web resources in the client's local file system
- **Example 2: Web proxy server**

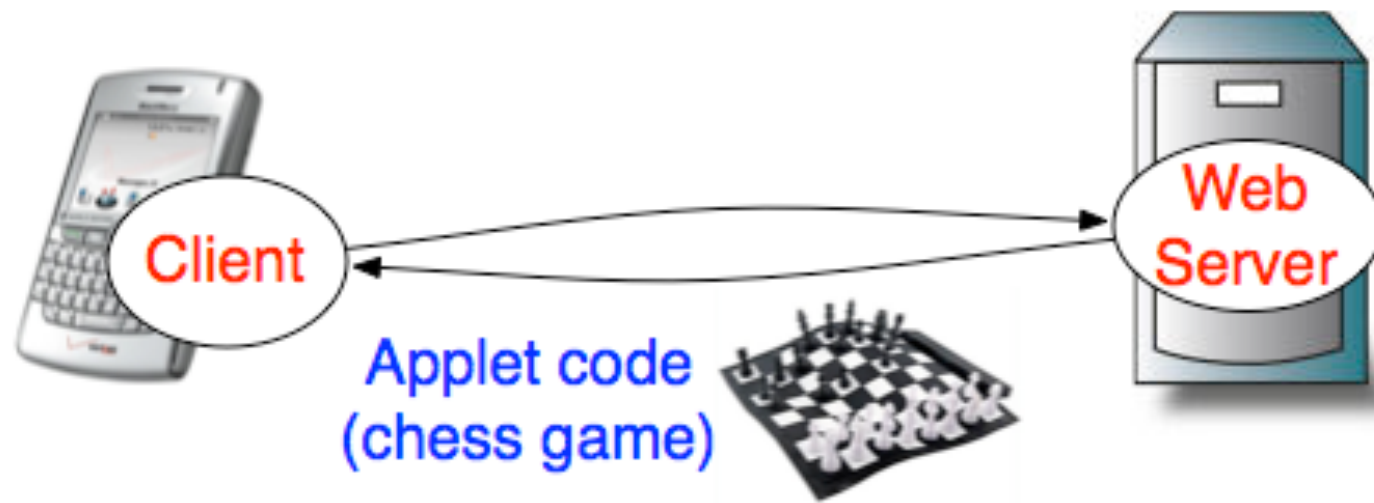
Purpose:

1. To keep machines behind it **anonymous** (mainly for security)
2. To **speed up** access to a resource (via caching)



Placement Strategy: Mobile Code

A) Client request results in the downloading of applet code



B) Client interacts with the applet

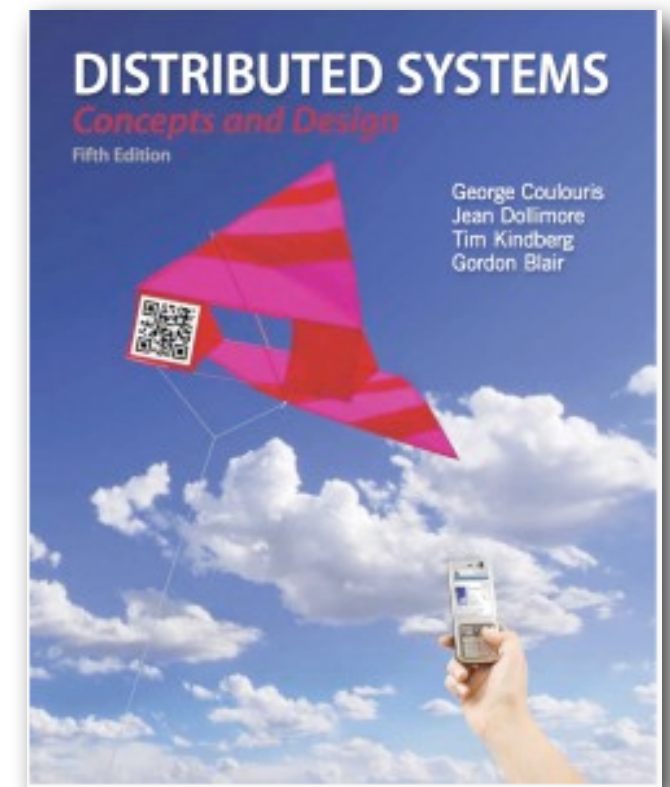


An **advantage** of running the downloaded code *locally* is that it can give **good interactive response** since it does not suffer from the delays or variability of bandwidth associated with network communication

Interaction Model



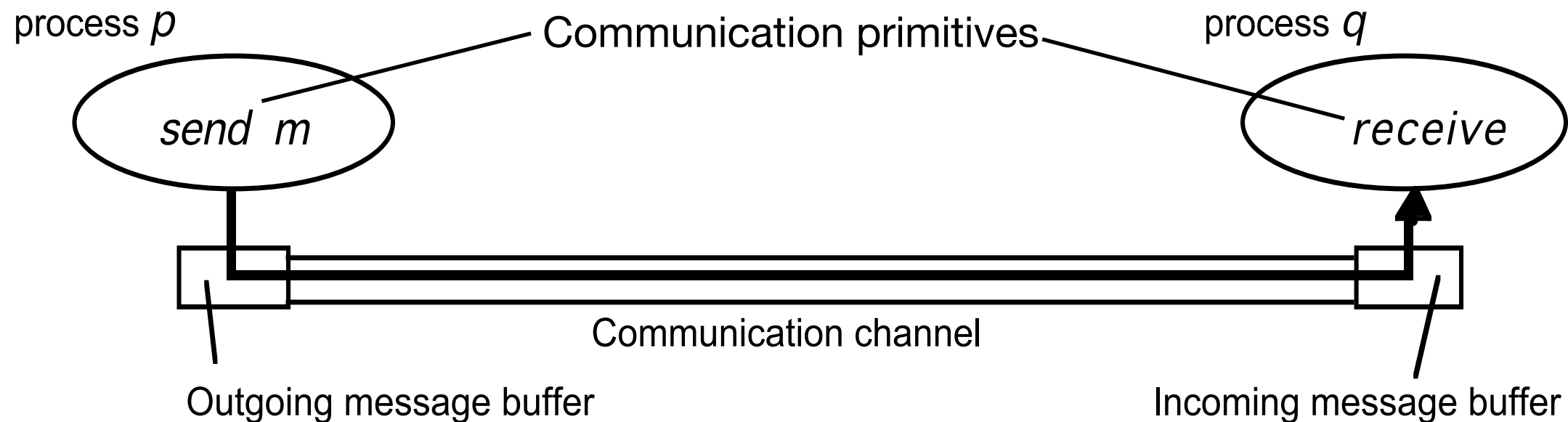
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Some Assumptions on Interacting Processes

- The **rate at which each process proceeds cannot** in general be predicted
- The **timing of the transmission of messages cannot** in general be predicted
- **Each process has its own state**, consisting of the set of data that it can access and update, including the variables in its program
- The **state belonging to each process is completely private** (that is, it cannot be accessed or updated by any other processes)

Processes and Communication Channels



- A process p performs a *send* by inserting the message m in its outgoing message buffer
- The communication channel transports m to q 's incoming message buffer
- Process q performs a *receive* by taking m from its incoming message buffer and delivering it
- Outgoing/incoming message buffers are typically provided by the operating systems

Factors Affecting Interacting Processes

- Communication performance
- It is impossible to maintain a single global notion of time

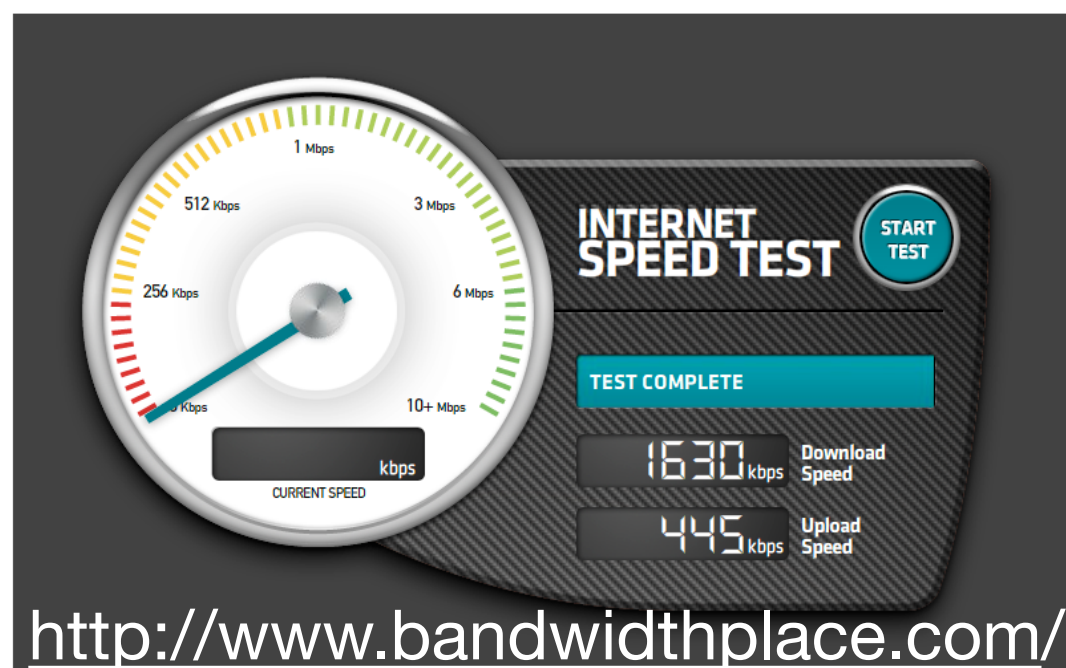


Performance of Communication Channels: Latency

- **Latency**: the delay between the start of a message's transmission from one process and the beginning of its receipt by another
- The latency includes:
 - ▶ The **time** taken for the **first of a string of bits** transmitted through the network **to reach its destination**
 - ▶ The **delay** in **accessing the network**, which increases significantly when the network is heavily loaded
 - ▶ The **time** taken by the **operating system communication services** at both the sending and receiving processes, which varies according to the current load of the operating systems

Performance of Communication Channels: Bandwidth

- The **bandwidth** of a computer network is the **total amount of information that can be transmitted over it in a given time**
- Usually expressed in **bit/s** or multiples of it (kbit/s, Mbit/s, etc)
- When a large number of communication channels are using the same network, they have to share the available bandwidth



56 kbit/s	Modem / Dialup
1.5 Mbit/s	ADSL Lite
1.544 Mbit/s	T1
10 Mbit/s	Ethernet
11 Mbit/s	Wireless 802.11b
44.736 Mbit/s	T3
54 Mbit/s	Wireless-G 802.11g
100 Mbit/s	Fast Ethernet
155 Mbit/s	OC3
300 Mbit/s	Wireless-N 802.11n
622 Mbit/s	OC12
1000 Mbit/s	Gigabit Ethernet
2.5 Gbit/s	OC48
9.6 Gbit/s	OC192
10 Gbit/s	10 Gigabit Ethernet

No Global Clock!!

- No single global notion of correct time.





Computer Clocks and Timing Events

- Each computer in a distributed system has its own internal clock, which can be used by local processes to obtain a value of the current time
- Therefore, two processes running on different computers can associate timestamps with their events
- However, **even if two processes read their clocks at the same time, their local clocks may supply different time values**
- This is because computer clocks drift from perfect time and, more importantly, their drift rates differ from one another
- **Clock drift rate:** rate at which a computer clock deviates from a perfect reference clock

Variants of the Interaction Model

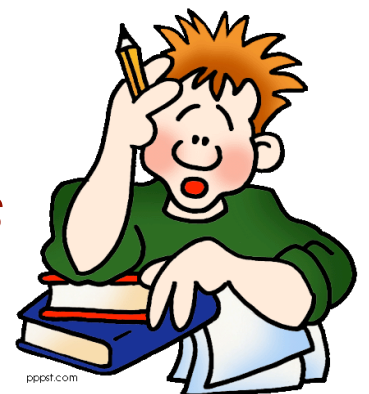
- In a distributed system it is hard to set time limits on the time taken for process execution, message delivery or clock drift
- Two **opposite extreme positions** provide a pair of **simple models**:
 - ▶ **Synchronous distributed systems**: strong assumption of time
 - ▶ **Asynchronous distributed systems**: no assumptions about time

Synchronous Distributed System

- A distributed system in which the following **bounds are defined**:
 - ▶ the **time to execute each step** of a process has known lower and upper bounds
 - ▶ each **message transmitted** over a channel is **received** within a known bounded time
 - ▶ each process has a **local clock** whose **drift rate from real time** has a known bound

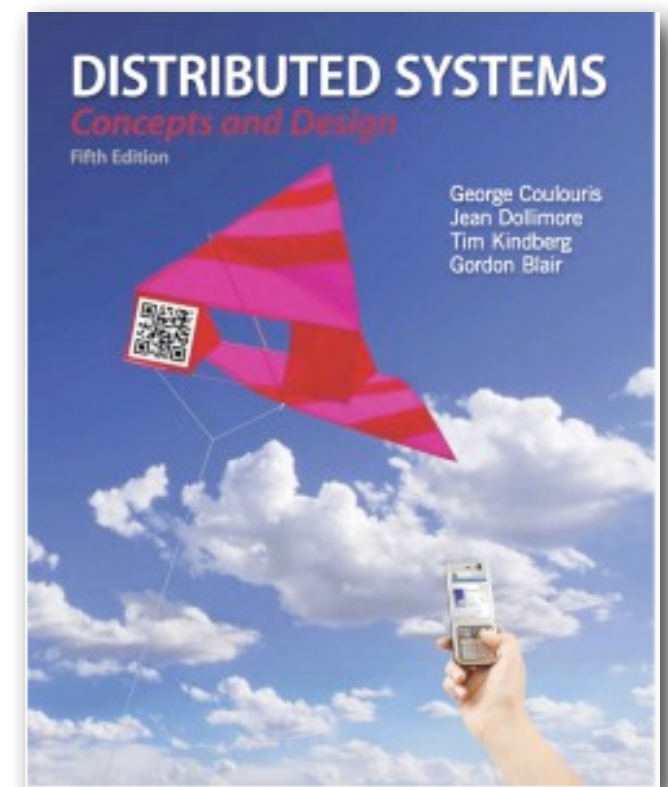
Asynchronous Distributed System

- A distributed system in which **there are no bounds on**:
 - ▶ **process execution speeds**: each step may take an arbitrarily long time
 - ▶ **message transmission delays**: a message may be received after an arbitrarily long time
 - ▶ **clock drift rates**: the drift rate of a clock is arbitrary
- This exactly models **the Internet**, in which **there is no intrinsic bound on server or network load** and therefore on how long it takes, for example, to transfer a file using ftp, or to receive an email message
- *Any solution that is valid for an asynchronous distributed system is also valid for a synchronous one.* **Why? What about the contrary?**

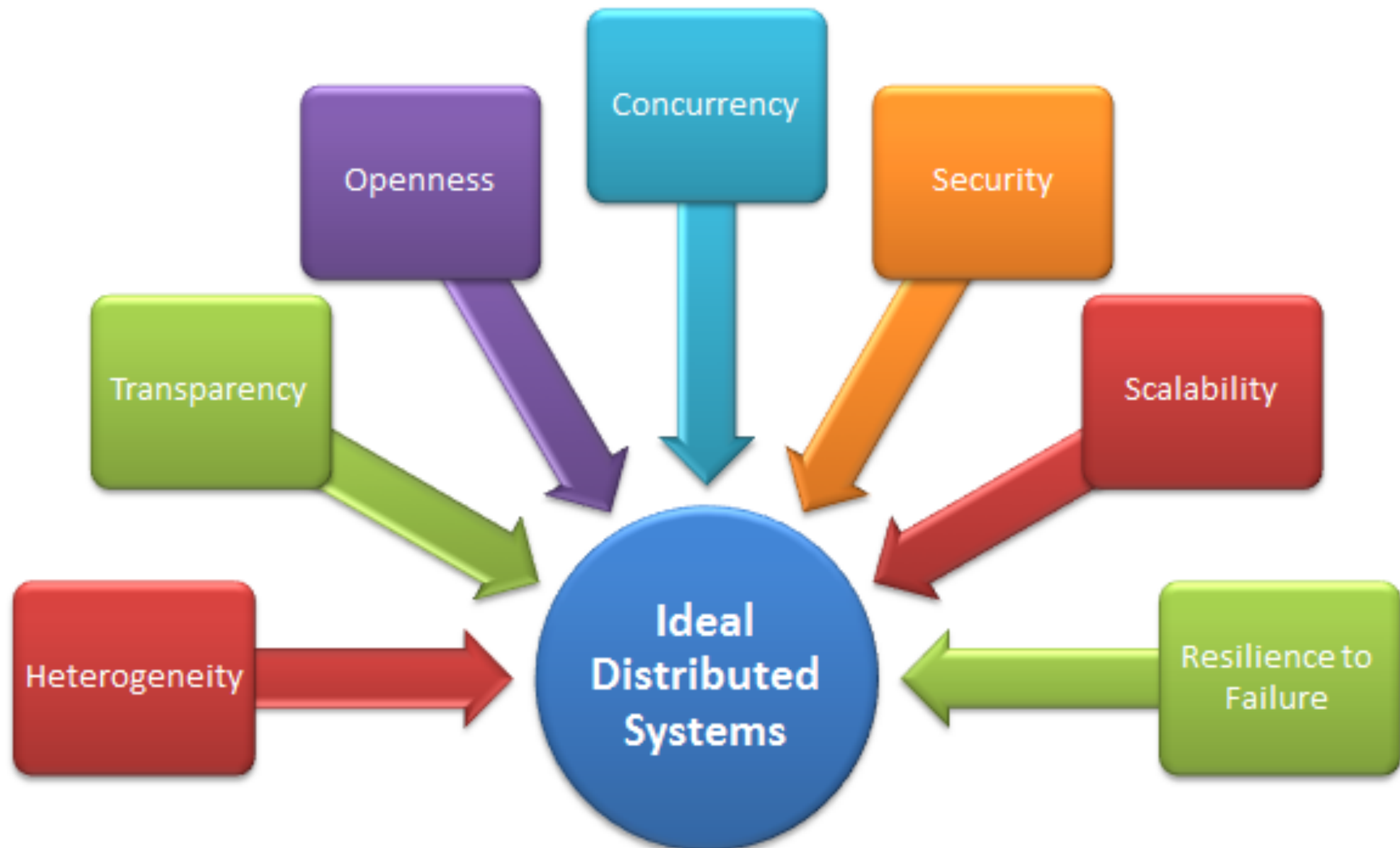


Design Challenges

1. Architectural Models
2. Interaction Model
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Design Challenges for Distributed Systems





Heterogeneity of Components

- **Heterogeneity** (i.e., **variety and difference**) applies to the following:

- ▶ networks
- ▶ computer hardware
- ▶ operating systems
- ▶ programming languages
- ▶ implementations by different developers

Heterogeneity can be addressed by means of:

- **protocols** (such as Internet protocols)
- **middleware** (software layer that provides a programming abstraction)

Example: Internet of Things (IoT)



- IoT is a complex, heterogeneous, distributed systems
 - Enormous differences in resources across tiers
 - Many programming languages, OSes, platforms, networks, ...
 - Specialized hardware



Openness

- The **openness of a computer system** is the characteristic that determines whether the system can be *extended* and *re-implemented* in various ways
- In **distributed systems** it is determined primarily by the degree to which new resource sharing services can be added and be made available for use by a variety of client programs
- Open distributed systems may be **extended**
 - ▶ at the **hardware level** by the addition of computers to the network
 - ▶ at the **software level** by the introduction of new services and the re-implementation of old ones



Example

- [Twitter](#) and [Facebook](#) have **API** that allows developers to develop their own software interactively

The screenshot shows the Twitter Developer documentation page. At the top is a purple navigation bar with links: Developer, Use cases, Products, Docs, More, and an Apply button. Below the navigation bar is a search bar with the text 'Search all documentation.' and a magnifying glass icon. The main heading is 'Docs'. On the left is a sidebar with a list of categories: Basics, Accounts and users, Tweets, Direct Messages, Media, Trends, Geo, Ads, Metrics, Publisher tools & SDKs, and Developer. The main content area has a sub-heading 'Below are some of the key areas where developers typically engage with the Twitt platform. For additional information, use the navigation to the left, or the search bc explore our documentation.' Below this are four featured sections, each with a title, a description, and a button: 'Ads API' (Getting started), 'Filter realtime Tweets' (Filter realtime Tweets), 'Search Tweets' (Search Tweets), and 'Direct Message API' (Build private experiences).

Developer Use cases Products Docs More Apply

Search all documentation.

Docs

Basics

Accounts and users

Tweets

Direct Messages

Media

Trends

Geo

Ads

Metrics

Publisher tools & SDKs

Developer

Below are some of the key areas where developers typically engage with the Twitt platform. For additional information, use the navigation to the left, or the search bc explore our documentation.

Ads API

Programmatically create and manage your ad campaigns

Getting started

Filter realtime Tweets

Get only the Tweets you need in realtime

Filter realtime Tweets

Search Tweets

Use the Search API to gather Tweets

Search Tweets

Direct Message API

Build personalized customer experiences with our Direct Message platform

Build private experiences

On This Page

APIs and SDKs

Find out how our APIs work and integrate our products quickly using SDKs for common languages and platforms.





Scalability

- A system is **scalable** if it will remain effective when there is a significant increase in the number of resources and the number of users
- The **Internet** provides an illustration of a distributed system in which **the number of computers and services has increased dramatically**

<i>Date</i>	<i>Computers</i>	<i>Web servers</i>	<i>Percentage</i>
1993, July	1,776,000	130	0.008
1995, July	6,642,000	23,500	0.4
1997, July	19,540,000	1,203,096	6
1999, July	56,218,000	6,598,697	12
2001, July	125,888,197	31,299,592	25
2003, July	~200,000,000	42,298,371	21
2005, July	353,284,187	67,571,581	19



Example

Challenge: preventing software resources running out

Example: **Internet IP addresses** (computer addresses in the Internet)

- In the late 1970s, it was decided to use **32 bits**, but the supply of available Internet addresses is running out
- For this reason, a new version of the protocol with **128-bit** Internet addresses is being adopted and this will **require modifications to many software components**
- How to solve this problem? **Not easy!**
 - ▶ It is **difficult to predict the demand** that will be put on a system years ahead
 - ▶ **Over-compensating for future growth may be worse than adapting to a change when we are forced to** (for instance, larger Internet addresses will occupy extra space in messages and in computer storage)

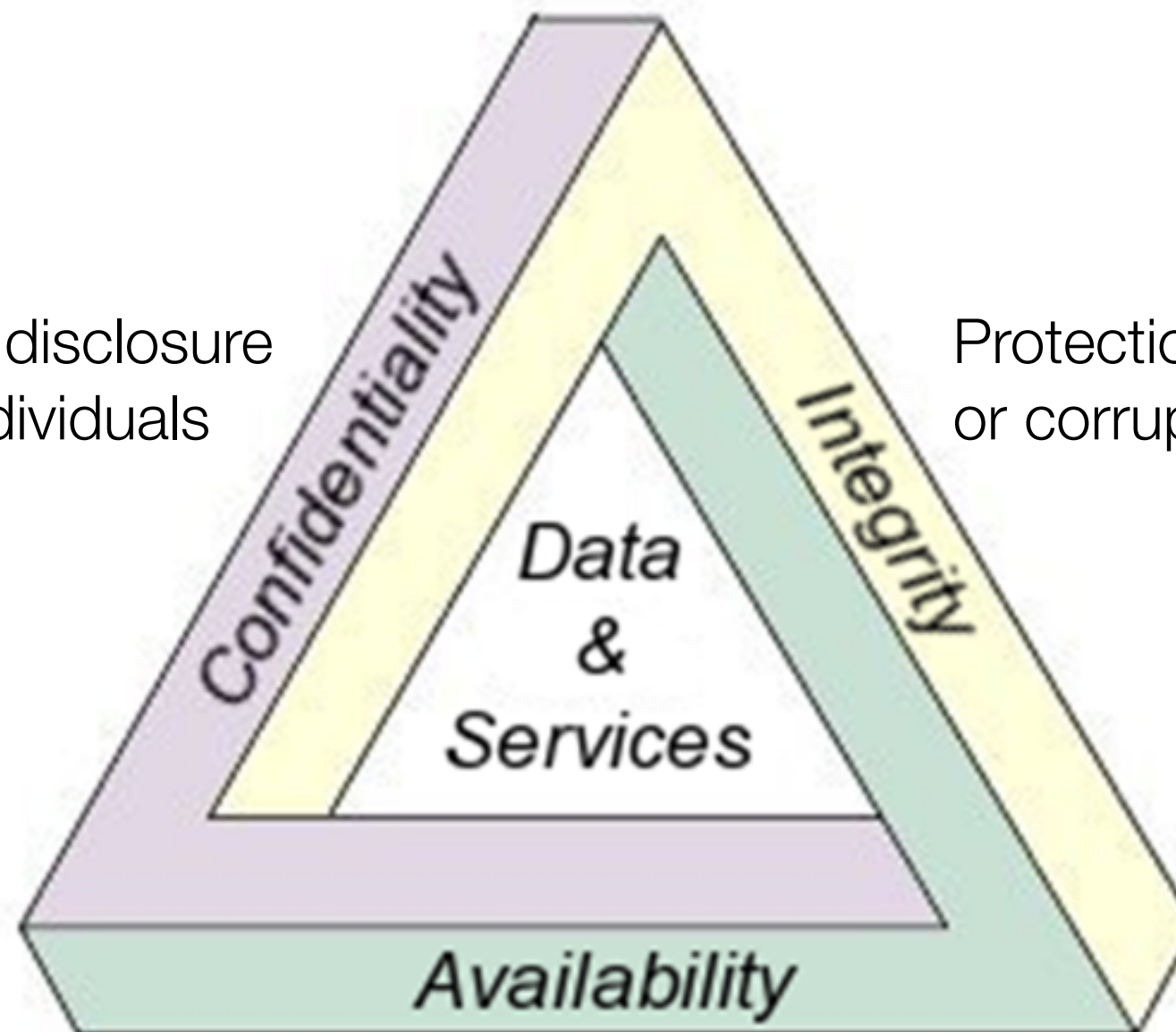


Another example: **Cloud Computing**

Security



Protection against disclosure
to unauthorized individuals



Protection against alteration
or corruption

Protection against interference with
the means to access the resources

Security Challenge: Denial of Service Attack

- A bad guy may wish **to disrupt a service** for some reason:
 - ▶ he **bombards** the service with such a **large number of pointless requests** that the **serious users are unable to use it**
- On August 6, 2009, Twitter was shut down for hours due to a DoS attack:



THU AUG 6TH

Ongoing denial-of-service attack 21 hours ago

We are defending against a denial-of-service attack, and will update status again shortly.

Update: the site is back up, but we are continuing to defend against and recover from this attack.

Update (9:46a): As we recover, users will experience some longer load times and slowness. This includes timeouts to API clients. We're working to get back to 100% as quickly as we can.

Update (4:14p): Site latency has continued to improve, however some web requests continue to fail. This means that some people may be unable to post or follow from the website.



DIGITAL INNOVATION

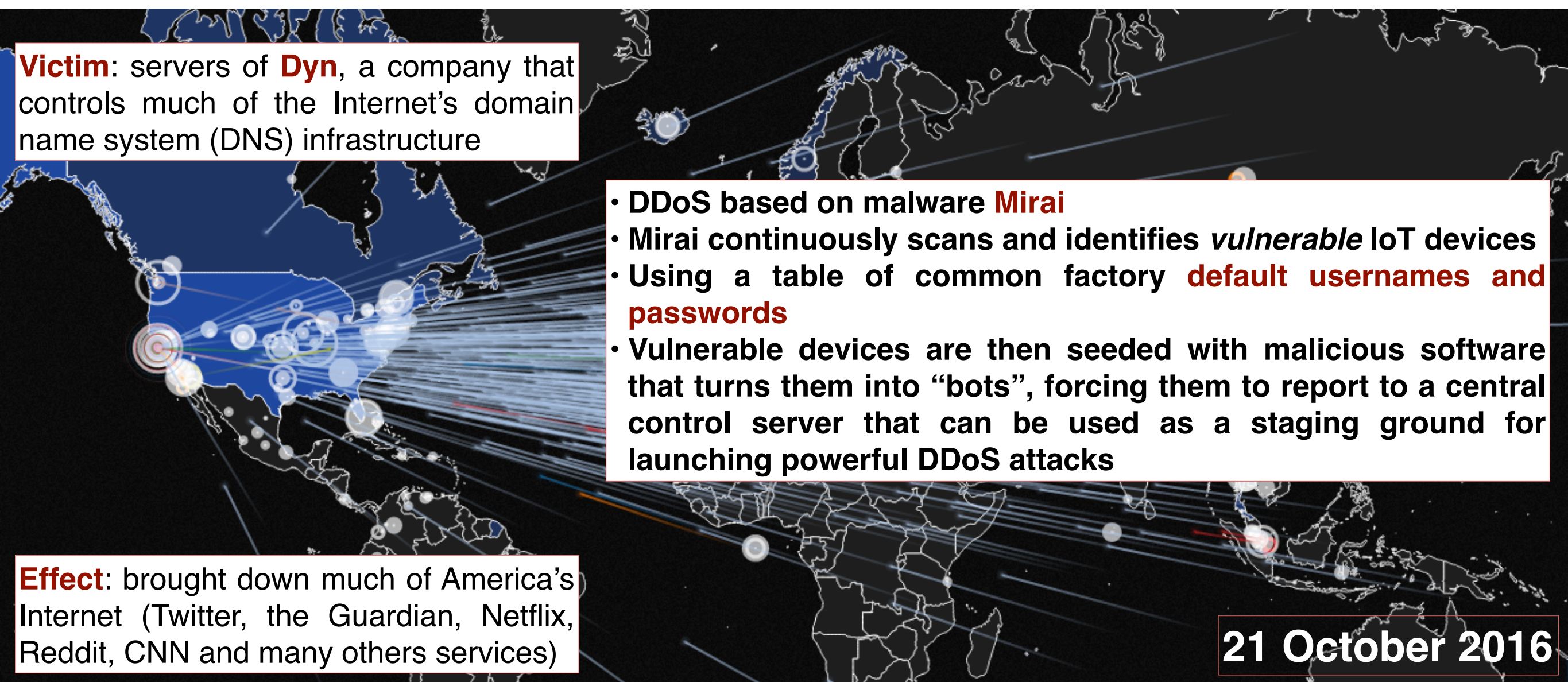
**BIG
DATA**

IoT
- EMBEDDED AI
- CONNECTIVITY

**5G
WIRELESS
NETWORKING**

CLOUD

Largest DDoS Attack Ever (~1.2Tbps)



Victim: servers of **Dyn**, a company that controls much of the Internet's domain name system (DNS) infrastructure

- DDoS based on malware **Mirai**
- Mirai continuously scans and identifies *vulnerable* IoT devices
- Using a table of common factory **default usernames and passwords**
- Vulnerable devices are then seeded with malicious software that turns them into “bots”, forcing them to report to a central control server that can be used as a staging ground for launching powerful DDoS attacks

Effect: brought down much of America's Internet (Twitter, the Guardian, Netflix, Reddit, CNN and many others services)

21 October 2016



Failure Handling

- Computer systems *sometimes* fail
- When faults occur in hardware or software, programs may produce incorrect results or they may stop before they have completed the intended computation
- Failures in distributed systems are partial:
 - ▶ any process, computer or network may fail independently of the others
 - ▶ some components fail while others continue to function
- Therefore the handling of failures in distributed systems is particularly difficult

Example: Consensus

Impossibility of Distributed Consensus with One Faulty Process

MICHAEL J. FISCHER

Yale University, New Haven, Connecticut

NANCY A. LYNCH

Massachusetts Institute of Technology, Cambridge, Massachusetts

AND

MICHAEL S. PATERSON

University of Warwick, Coventry, England

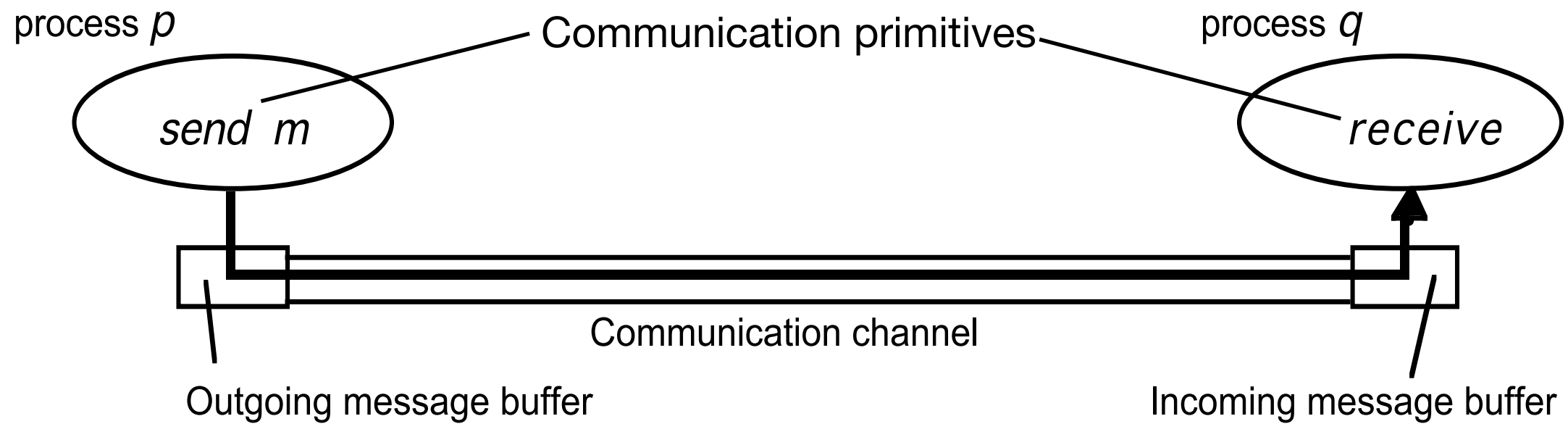
Abstract. The consensus problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value. In this paper, it is shown that every protocol for this problem has the possibility of nontermination, even with only one faulty process. By way of contrast, solutions are known for the synchronous case, the “Byzantine Generals” problem.



Failure Model

- The **failure model** defines the ways in which failures may occur in order to provide an understanding of the effects of failures
- Example of **taxonomy of failures** [Hadzilacos and Toueg, 1994]:
 - ▶ **Omission failures**: a process or communication channel fails to perform actions that it is supposed to do
 - ▶ **Arbitrary failures**: any type of error may occur
 - ▶ **Timing failures**: applicable in synchronous distributed systems

[Failure Model] Omission Failures



Class of failure	Affects	Description
Crash	Process	Process halts prematurely and remain halted.
Omission	Channel	A msg inserted in an outgoing msg buffer never arrives at the other end's incoming message buffer.
Send-omission	Process	A process completes a 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.

[Failure Model] Arbitrary Failures

- The term *arbitrary* or *Byzantine failure* is used to describe the **worst possible failure semantics**, in which **any type of error may occur**
- **Arbitrary failure of a process**: the process arbitrarily omits intended processing steps or takes unintended processing steps
- **Communication channel arbitrary failures**: message contents may be corrupted or non-existent messages may be delivered or real messages may be delivered more than once

Class of failure	Affects	Description
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.

[Failure Model] Timing Failures

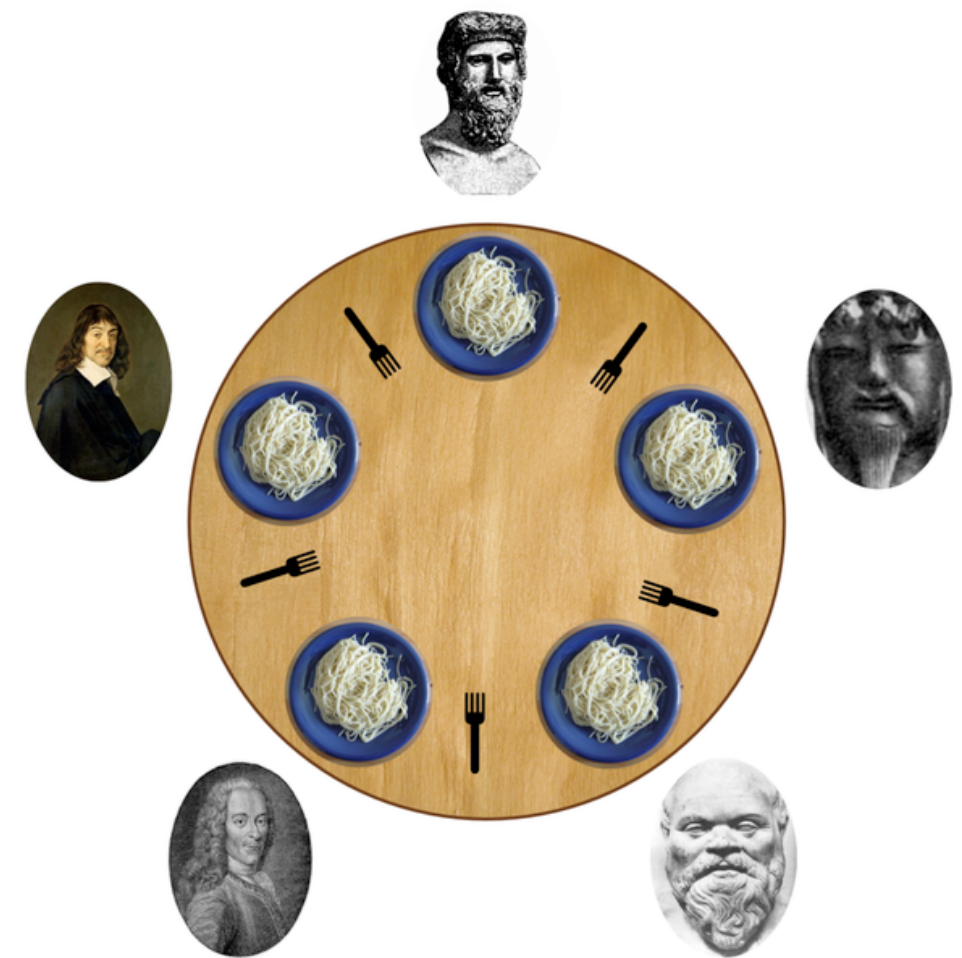
- Timing failures are applicable in **synchronous** distributed systems, where time limits are set on process execution time, message delivery time and clock drift rate

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.

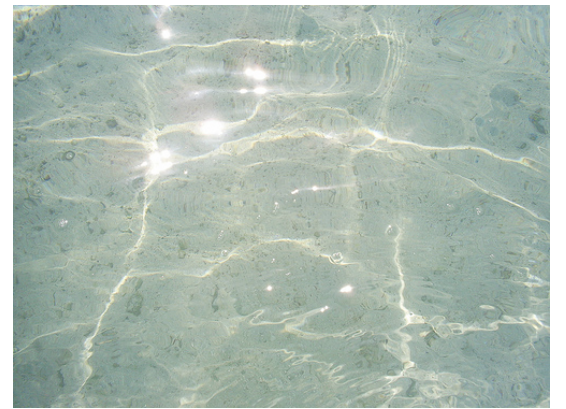
- In an **asynchronous** distributed systems, an overloaded server may respond too slowly, but *we cannot say that it has a timing failure since no guarantee has been offered*

Concurrency

- Both services and applications provide resources that can be shared by different clients in a distributed system
- There is therefore a possibility that **several clients** will attempt to access a **shared resource** at the **same time**
- **Each resource** (servers, Web resources objects in applications, ...) **must be designed to be safe in a concurrent environment**



Dining Philosophers Problem

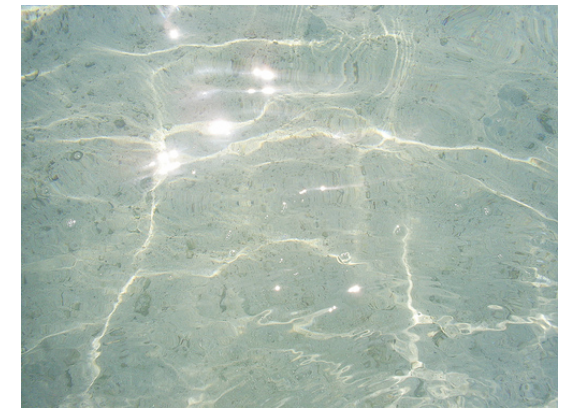


Transparency

- **Transparency**: the concealment from the user and the application programmer of the separation of components in a distributed system, so that the system is perceived as a whole rather than a collection of independent components
- **Aim**: to make certain aspects of distribution invisible to the application programmer so that they need only be concerned with the design of their particular application
- The ANSA Reference Manual and the International Organization for Standardization's Reference Model for Open Distributed Processing (RM-ODP) identify 8 forms of transparency

Example: *MAKE* command

- When a UNIX user types *make* to recompile a large number of files in a directory, he need not be told that all the compilations are proceeding in parallel on different machines and are using a variety of file servers to do it
- In terms of commands issued from the terminal and results displayed on the terminal, *the distributed system can be made to look just like a single-processor system*



Transparencies

Network transparency

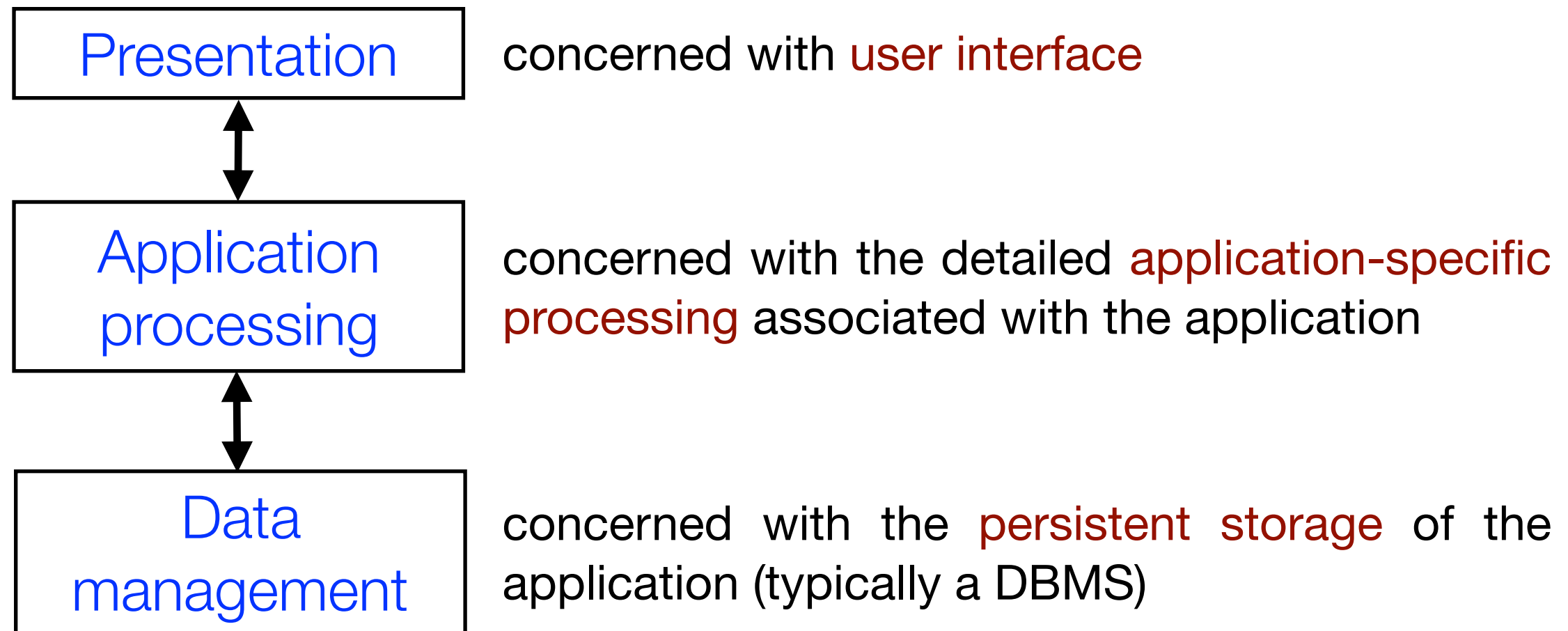
Access Transparency	Enables local and remote resources to be accessed using identical operations
Location Transparency	Enables resources to be accessed without knowledge of their physical or network location (for example, which building or IP address)
Concurrency Transparency	Enables several processes to operate concurrently using shared resources without interference between them
Replication Transparency	Enables multiple instances of resources to be used to increase reliability and performance without knowledge of the replicas by users or application programmers
Failure Transparency	Enables the concealment of faults, allowing users and application programs to complete their tasks despite the failure of hardware or software components
Mobility Transparency	Allows the movement of resources and clients within a system without affecting the operation of users or programs
Performance Transparency	Allows the system to be reconfigured to improve performance as loads vary
Scaling Transparency	Allows the system and applications to expand in scale without change to the system structure or the application algorithms

PROBLEM

Design of a Client-Server System for Banking

Problem: Design of a Client-Server System

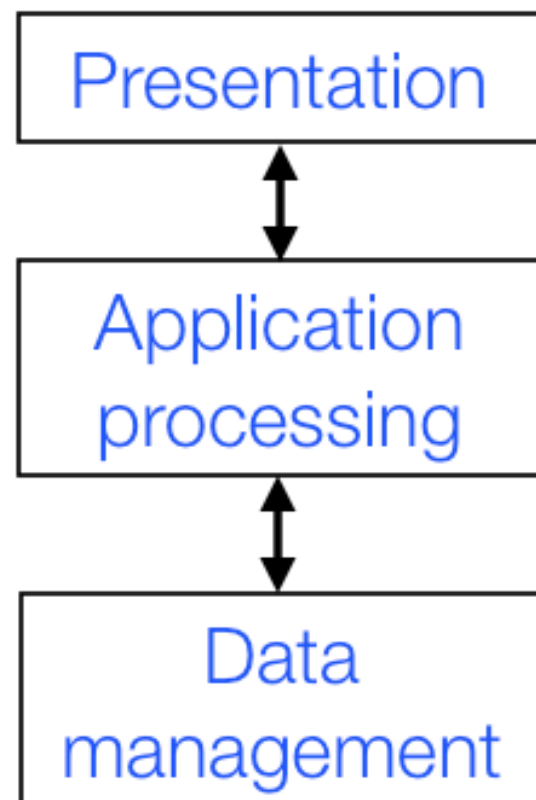
- **Input:** an informal description of an application (e.g., banking application)



- **Output:** client-server implementation of the application

Solution 1: Two-Tier Client-Server Architecture

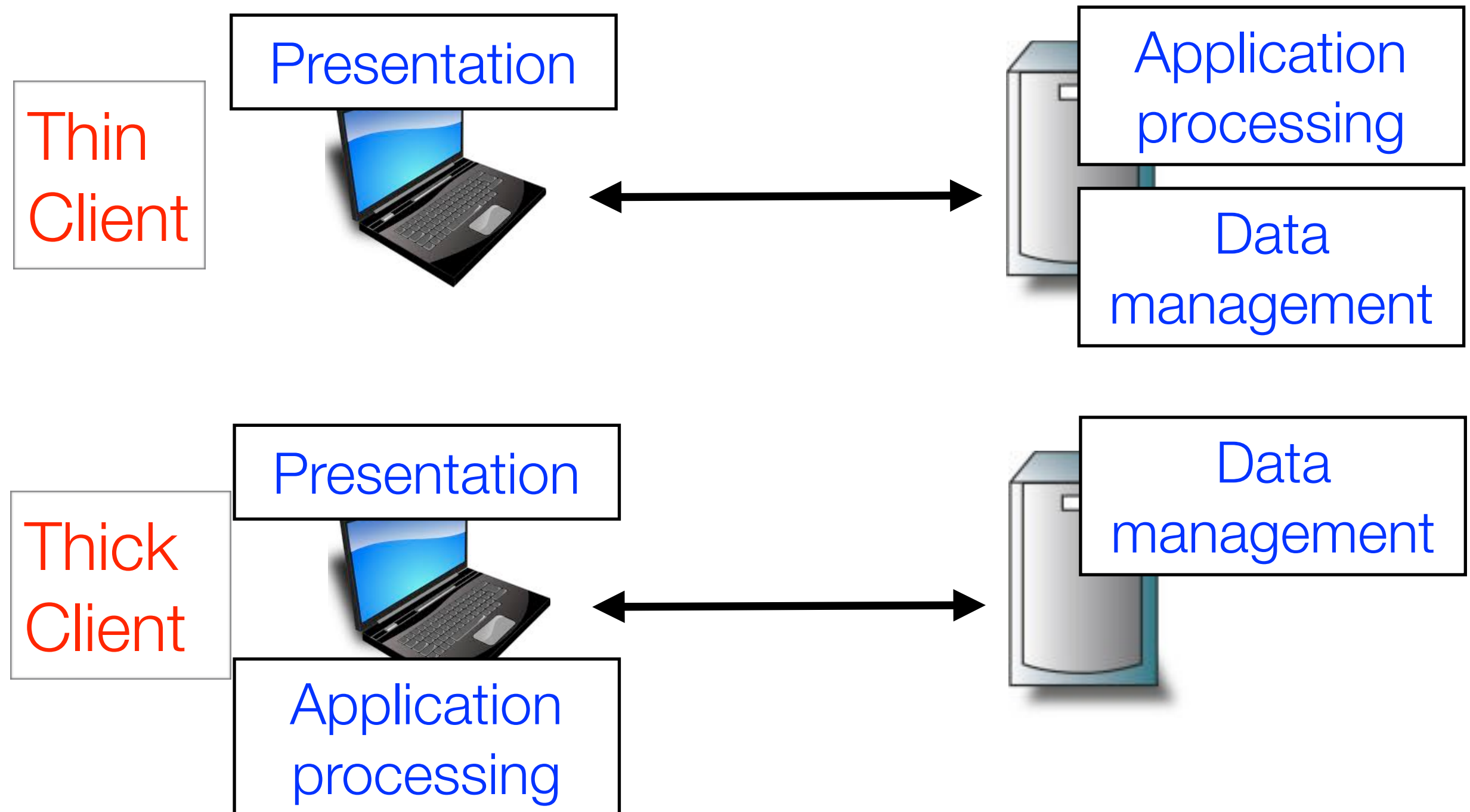
- Application organized as **a server** and **a set of clients**
- **Two kinds** of machines: **client machines** and **server machines**



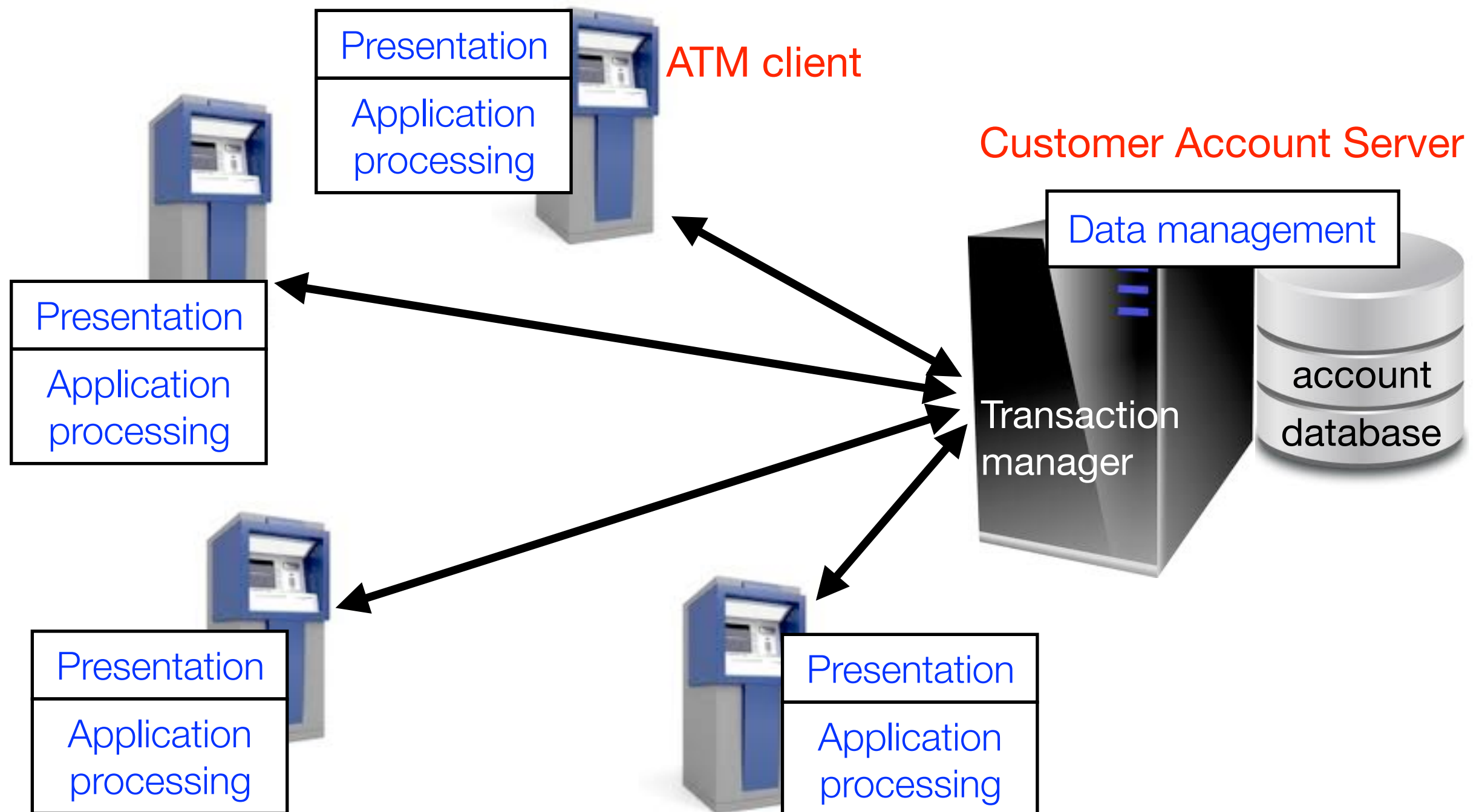
*how to map
3 application layers
into a 2-tier architecture?*



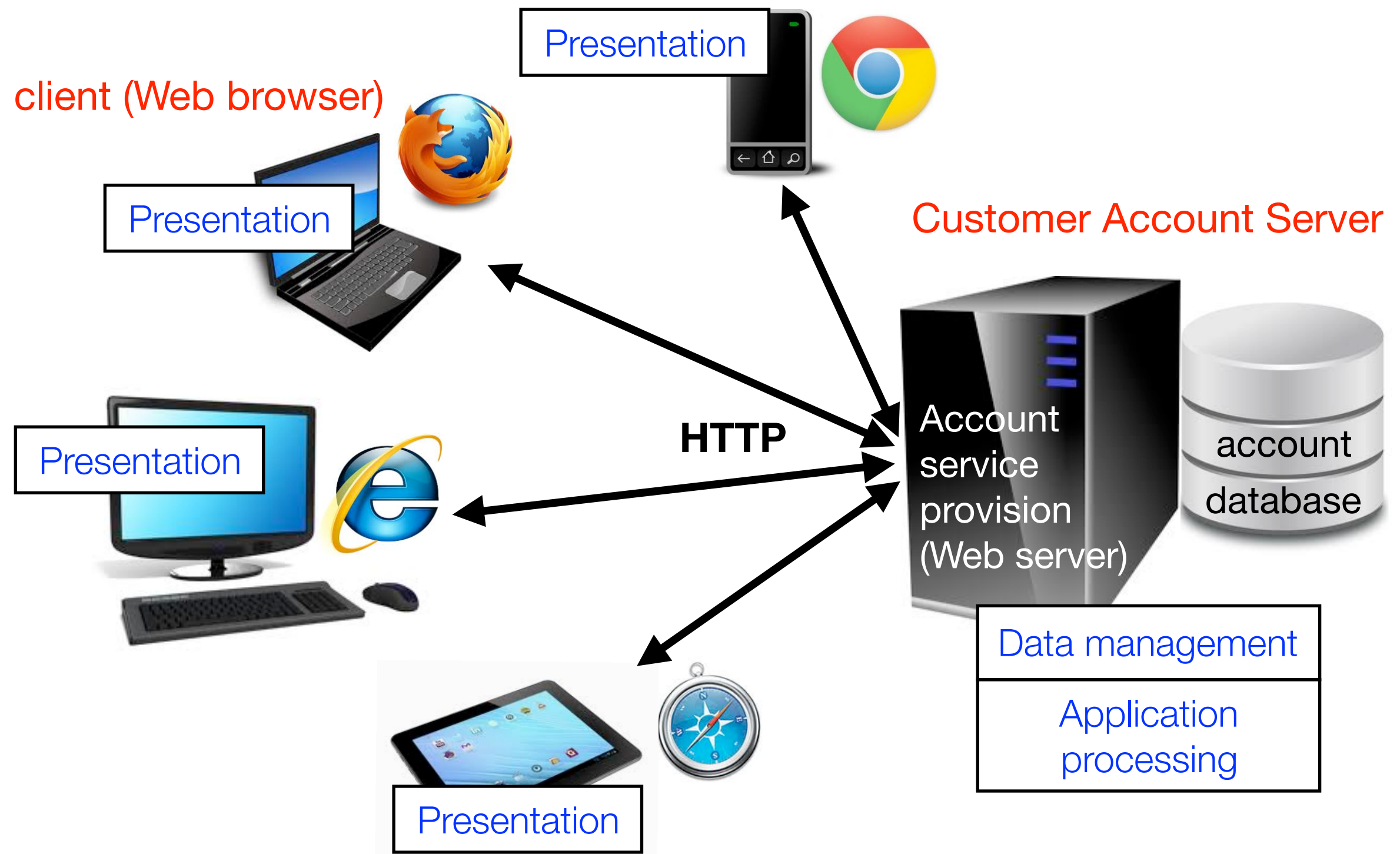
Thin VS Thick Client Model



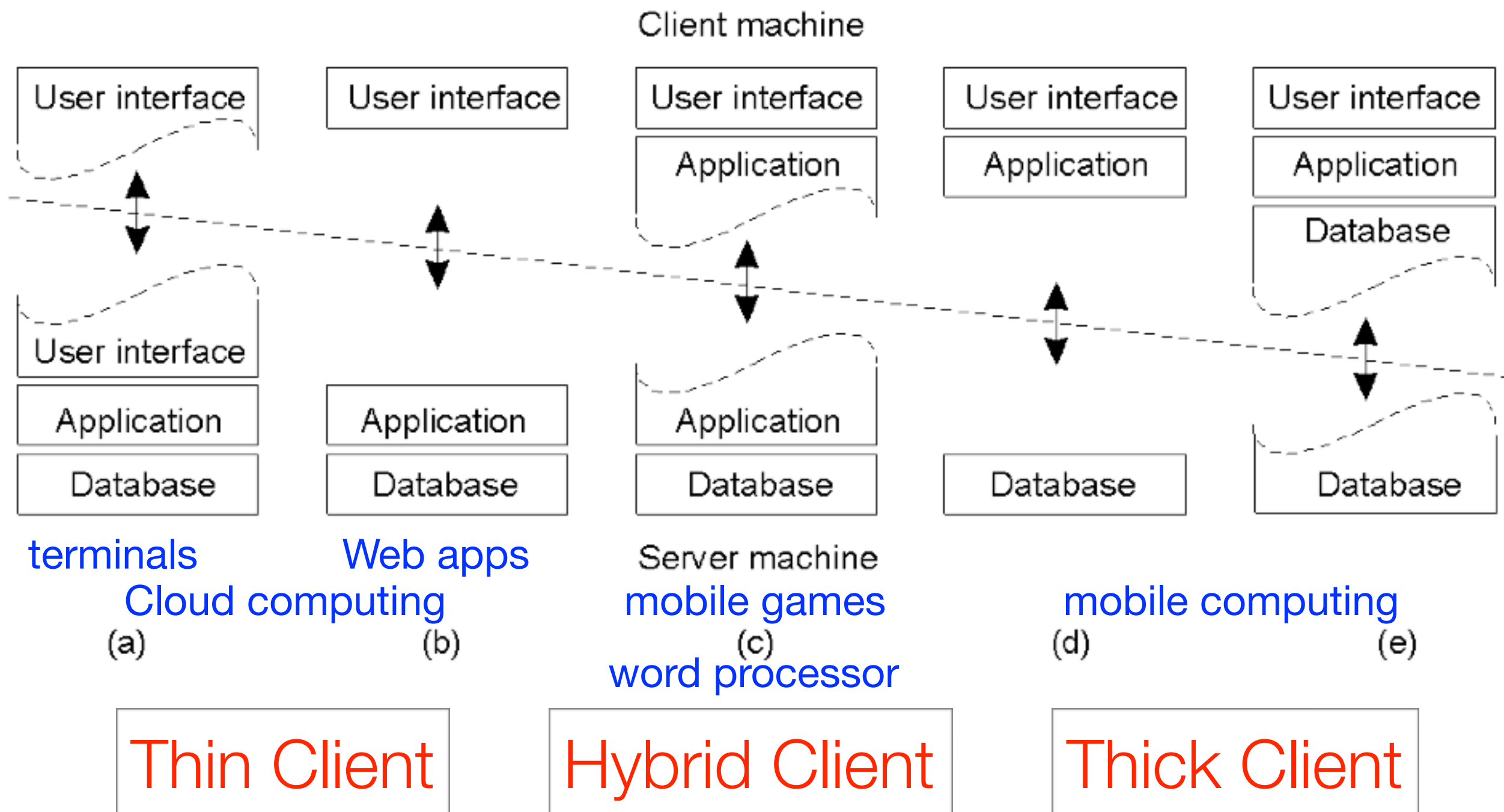
Example of Thick Client: ATM Banking System



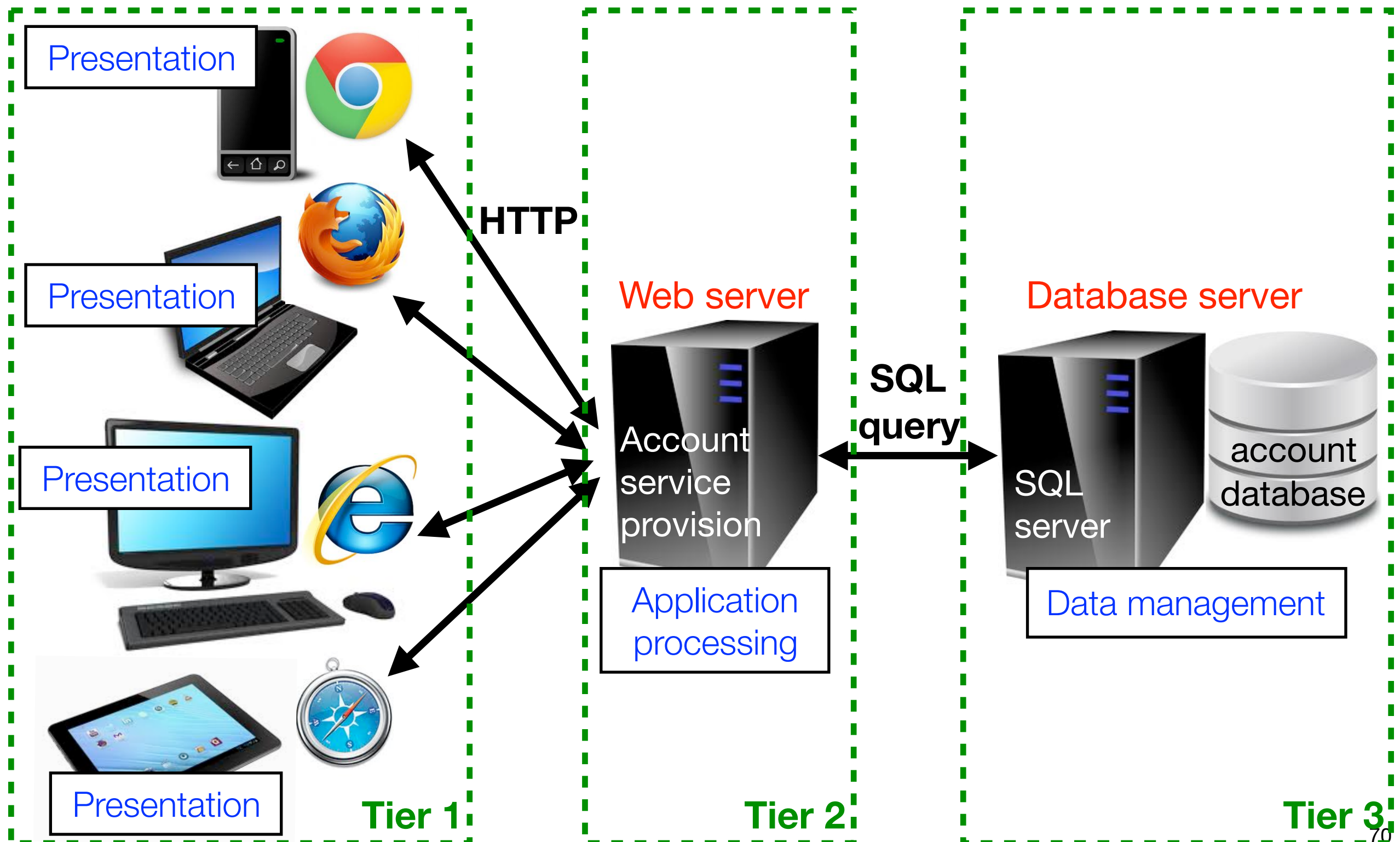
Examples of Thin Client: Internet Banking System



Alternative Two-Tier Client Server Organizations



Internet Banking System... in Practice



Thin or Thick? Thin



- Devices significantly enhanced with a **plethora of networked services**
- Access to **legacy systems**
- **System management and administration**
 - from **admin perspective**: system maintenance, security
 - from **user perspective**: not hassle with administrative aspects or constant upgrades
- More **security**
- **Green IT** (power saving --> cost saving)

pros

- Heavy processing load on both **server** and **network**
- **Less client-perceived performance** (in highly interactive graphical activities such as CAD and image processing)
- Need to be **always connected**

cons

Thin or Thick? Thick



- Better client-perceived performance (especially, in terms of image & video processing)
- (Partly) available offline
- Distributed computing (no single point of failures)
- Devices are becoming ever faster and cheaper:
what is the point of off-loading computation on a server when the client is amply capable of performing it without burdening the server or forcing the user to deal with network latencies?

pros

- System management and related costs
- Having more functionality on the client makes client-side software more prone to errors and more dependent on the client's underlying platform

cons

Use of Client–Server Architectural Patterns

Two-tier client-server architecture with thin clients

- Legacy system applications that are used when separating application processing and data management is impractical; clients may access these as services
- Computationally intensive applications such as compilers with little or no data management
- Data-intensive applications (browsing and querying) with non-intensive application processing (example: browsing the Web)

Two-tier client-server architecture with fat clients

- Applications where application processing is provided by off-the-shelf software (e.g., Microsoft Excel) on the client
- Applications where computationally intensive processing of data (e.g., data visualization) is required
- Mobile applications where internet connectivity cannot be guaranteed
- Some local processing using cached information from the database is therefore possible

Multi-tier client-server architecture

- Large-scale applications with hundreds or thousands of clients
- Applications where both the data and the application are volatile
- Applications where data from multiple sources are integrated

Homework

Consider a hypothetical car hire company and sketch out a three-tier solution to the provision of their underlying distributed car hire service. Use this to illustrate the benefits and drawbacks of a three-tier solution considering issues such as performance, scalability, dealing with failure and also maintaining the software over time.