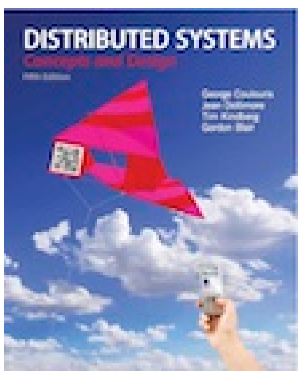
Slides for Chapter 2:
System Models



From **Coulouris, Dollimore, Kindberg and Blair**

Distributed Systems:
Concepts and Design

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Introduction [2.1]

- Real-world systems should (ideally) be designed to function in widest possible range of circumstances (incl. difficulties and threats)
- Chap2: how properties and design issues of DSs can be captured and analyzed with descriptive models
  - **Physical models:** HW composition of computers (and devices) and networks that interconnect them
  - **Architectural models**: describe w.r.t. computational tasks done by computational elements (single or aggregate) connected by networks
  - **Fundamental models**: abstract perspective examining an individual aspect of a distributed system
    - **Interaction models** (struct+seq of elements' comms), **failure models**, **security models**

Difficulties and Threats for DSs

- Many problems face designers of DSs!
- Widely varying modes of use
  - Workload
  - Some parts disconnected or with flaky connectivity
  - Some need high bandwidth and/or low latency
- Wide range of system environments
  - Heterogenieties discussed earlier
  - Networks vary widely in performance (statically and dynamically)
  - Scale from tens to millions of computers

Difficulties and Threats for DSs (cont.)

- Internal problems
  - Non-synchronized clocks
  - Conflicting data updates
  - *Many* modes of HW+SW failure for individual components
- External threats: attacks on
  - **C**onfidentiality
  - **I**ntegrity
  - **A**vailabiilty (incl. DoS attacks)

Physical Models [2.2]

- **Physical model**: representation of underlying HW in a DS that abstracts away specific details of techs (comp+net)
  - Baseline model (minimal): extensible set of computer nodes interconnected by a network that passes messages
  - Beyond this, 3 generations of DSs: early, internet-scale, contemporary
- Early DSs:
  - Late 70s and early 80s, when Ethernet came
  - Typically 10-100 nodes connected by a LAN, sharing files+printers
  - Internet: limited connectivity, low bandwidth; email, file transfer
  - Mostly homogeneous, openness not a concern (or known!)
  - QoS in its infancy (lotsa research started)

Internet-Scale DSs

- Emerged in 1990s (google 1996): dramatic growth of Internet (broadband)
- Early DSs model extended to systematically expoit "network of networks" (internet)
- Large # nodes, global reach and use
- Significant heterogeneity
- Lead to open standards and middleware (started late 70s)
- QoS greatly improved
- Nodes typcailly
  - Desktop computers
  - Discrete (not embedded within other physical entities)
  - Autonomous: endependent of other computers largely

Contemporary DSs

- Mobile computing, ergo need service discovery and spontaneous interoperation
- Ubiquitous computing, ergo handle where computers are embedded in everyday objects and in surroundings
- Cloud computing and clusters: autonomous nodes ➔ cluster that provides a given service
- Result: huge increase in heterogeneity (all types)

Figure 2.1
Generations of Distributed Systems

Distributed systems:	*Early*	*Internet-scale*	*Contemporary*
Scale	Small	Large	Ultra-large
Heterogeneity	Limited (typically relatively homogenous configurations)	Significant in terms of platforms, languages and middleware	Added dimensions introduced including radically different styles of architecture
Openness	Not a priority	Significant priority with range of standards introduced	Major research challenge with existing standards not yet able to embrace complex systems
Quality of service	In its infancy	Significant priority with range of services introduced	Major research challenge with existing services not yet able to embrace complex systems

Distributed System-of-Systems (SoS)

- System (esp. software) organized into system of systems (analogy to internet: network of networks)
- Subsystems subsystems are almost independent systems (architecturally) assembled for a particular task
- Composition issues for QoS are huge (DARPA 90s, EC 2012)
- **Emergent properties**: when simple(r) subsystems form complex collective behaviors
  - Biological examples: flock of birds or school of fish
  - New and subtle behaviors emerge
  - Observable in many structures: hierarchies, decentralized (e.g., marketplace)
  - Key problem in SOSs (EC 2012+)

Architectural Models [2.3]

- Structure a system in terms of separately specified components and their relationships
- Goal: ensure structure meets present & (likely) future req.
- Concerns: reliability, manageability, adaptability, cost-effectiveness
- Three-phase buildup of concepts (*long* sub-chapter!)
  - Core underlying architectural elements [2.3.1]
  - Composite arch. patterns usable in isolation or combination [2.3.2]
  - Middleware platforms supporting programming styles emerging from [2.3.1] and [2.3.3]

Architectural Elements [2.3.1]

Need to consider 4 key questions:

1. What **entities** are communicating in the DS?
2. What **communication paradigm**/pattern do entities use?
3. What **roles and responsibilities** do entities have
   - May change!
4. How are entities mapped onto physical infrastructure (**placement**)

Communicating Entities

- System perspective: processes are communicating
  - Simple environments (sensors): no processes, so entities≡nodes
  - Most environments: threads, so technically the endpoints
- Programming perspective: more problem-oriented abstr.
  - Objects: coherent packaging of code+data, multiple instances
    - Problem-oriented abstractions, units of decomposition
    - Access via interfaces (spec. in IDL)
    - Distributed objects more in Chap 5, 8
  - Components
    - Similar to objects: code+data, interfaces
    - Also specify assumptions made (needed external components/interfaces) … i.e., dependencies made explicit … better "contract" for constructing systems
  - Web services (access objects/components via WWW)
    - Rather ugly underlying technologies at time

Communication Paradigms

- 3 kinds: interprocess comm., remote invoc., indirect comm.
- **Interprocess communication** (IPC)
  - Low-level support for communication
  - Usually socket API

Remote Invocation

- Most common (arguably), two-way exchange; buildup…
- **Request-reply protocols** (application level)
  - Pattern imposed on underlying message passing to support client-server
  - Client app code sends message with operation, params, bookeeping in request message
  - Server sends msg with bookkeeping, params in reply message
  - Low-level, typically simple embedded systems w/strong RT needs
- **Remote procedure call** (RPC)
  - Make a remote call look (almost) like a local call
  - Supports many transparencies and heterogeneities
  - Directly supports client-server computing at higher level than RRPs

Remote Invocation

- **Remote method invocation (RMI)**
  - Extends procedural RPC to object-oriented programming
  - Multiple object instances: can pass object refs/IDs as params
  - Tighter integration than RPC into the language

Decoupled communication

- IPC, RRP, RPC, RMI all have explicit receivers/endpoints for each direction of comm
  - Senders must know (or obtain through name service) receivers IDs; receivers often know senders
  - Sender and receiver must both exist at same time
  - Can be less flexible than desirable for some apps
- **Space uncoupling**: senders do not need to know who sending to
- **Time uncoupling**: senders and receivers don't have to have overlapping lifetimes (exist at same time)
- Uncouplings support **indirect communication** (Chap 6)

Overview of Indirect Communication Techniques

- **Group communication**
  - 1:many comms with group ID
  - Recipients join group, senders send to group
  - Groups often maintain membership, handle member failures
  - IP multicast trivial example, but many more fancier ones
- **Publish-subscribe**
  - Producers (publishers) send out info, publishers get it
  - Intermediate service is in between
  - Can subscribe based on data: topics

Overview of Indirect Communication Techniques (cont.)

- **Message queues**
  - Senders send to a specific queue, point-to-point
  - Consumers can get from queue (or be notified if new items)
- **Tuple spaces**
  - Structured data: (int, float, string, …) with a given signature
  - Processes can read or remove tuples, can match values of some/all fields in tuple
- **Distributed shared memory (DSM)**
  - Abstraction of a shared address space or data structures therein
  - Lots of research in the late 80s and 90s, died out mostly

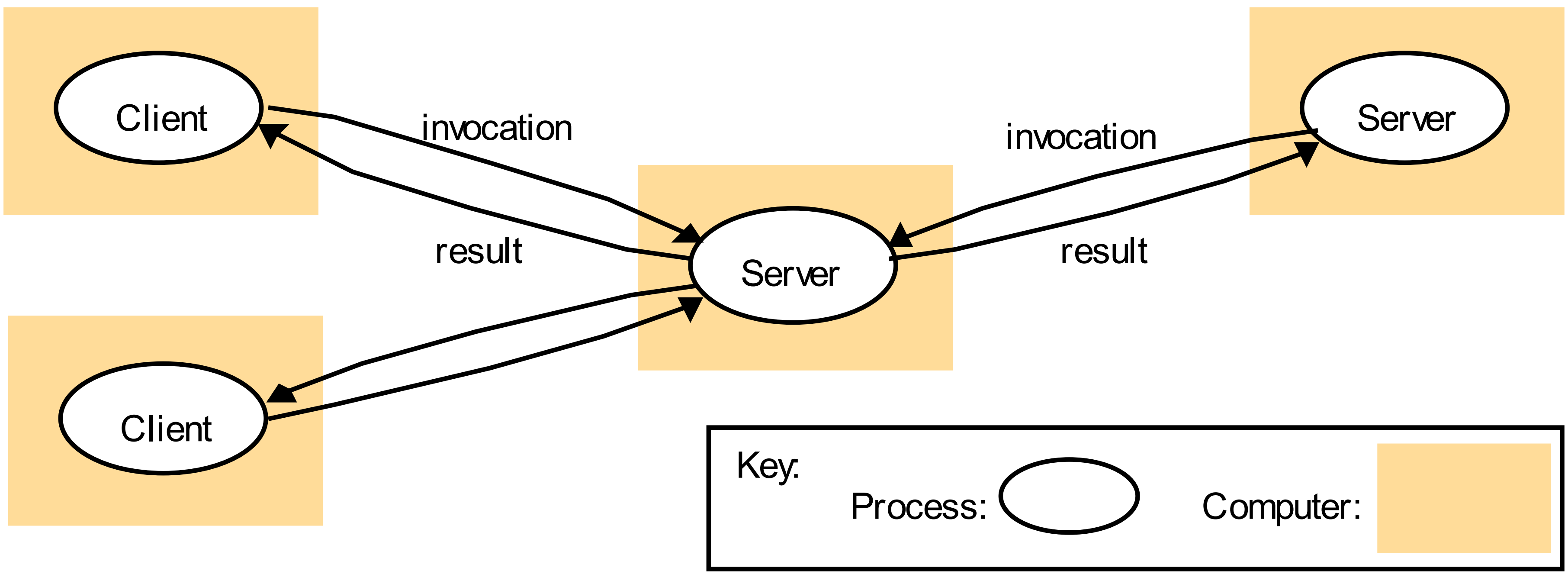
Figure 2.2
Communicating entities and communication paradigms

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

Roles and Responsibilities

- Issue: what role does a given entity take
- **<u>Client-server</u>**
  - Most widely studied and deployed
  - Client sends request to server, which replies
  - Can be either RPC or RMI
  - C/S w.r.t a given interaction: A→B→C means B client and server
- **<u>Peer-to-peer</u>** (P2P): scales better, no centralized service
  - Observation: use not (just) centralized servers from a service, but end user can support that service (plenty of resources at edges!)
  - All entities are equals (and none/few “more equal than others”)
  - Entities run same program with same interfaces
  - Examples: BitTorrent, Skype (originally), ..

Figure 2.3
Clients invoke individual servers



Placement

- How to map entities (objects, services, …) onto physical infrastructure
- Must take into account many things:
  - Patterns of communication
  - Reliability and current load of given machines
  - (Often) strong knowledge of application/service
- No optimal solutions, only strategies that help
  - Mapping services onto multiple servers
  - Caching
  - Mobile code
  - Mobile agents

Placement (cont)

- Mapping services to multiple servers (Fig 2.4)
- Caching
  - Cache: a store of recently used data objects closer or at a client
  - Examples?
  - Lotsa bookkeeping passed around to track updates/staleness/etc
  - If client requests stale object, it is fetched
- Mobile code
  - Applets …. And client-side (edge) resources usually plentiful
- Mobile agents
  - Agent: a running program (code+data) that travels to carry out a task for some entity, and returns results
  - Difference from mobile code?

Figure 2.4
A service provided by multiple servers (servers are P2P)

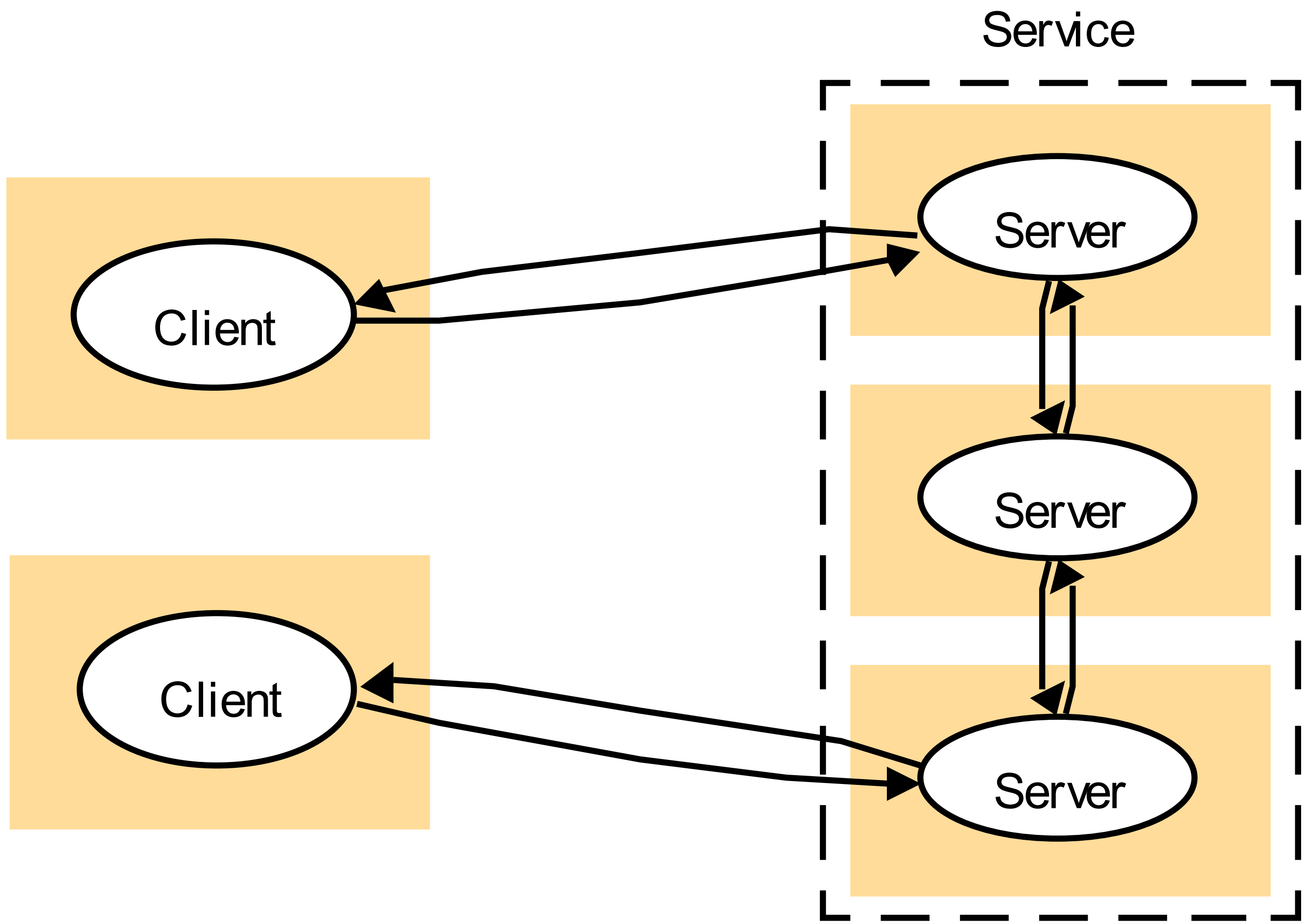


Figure 2.5
Web proxy server

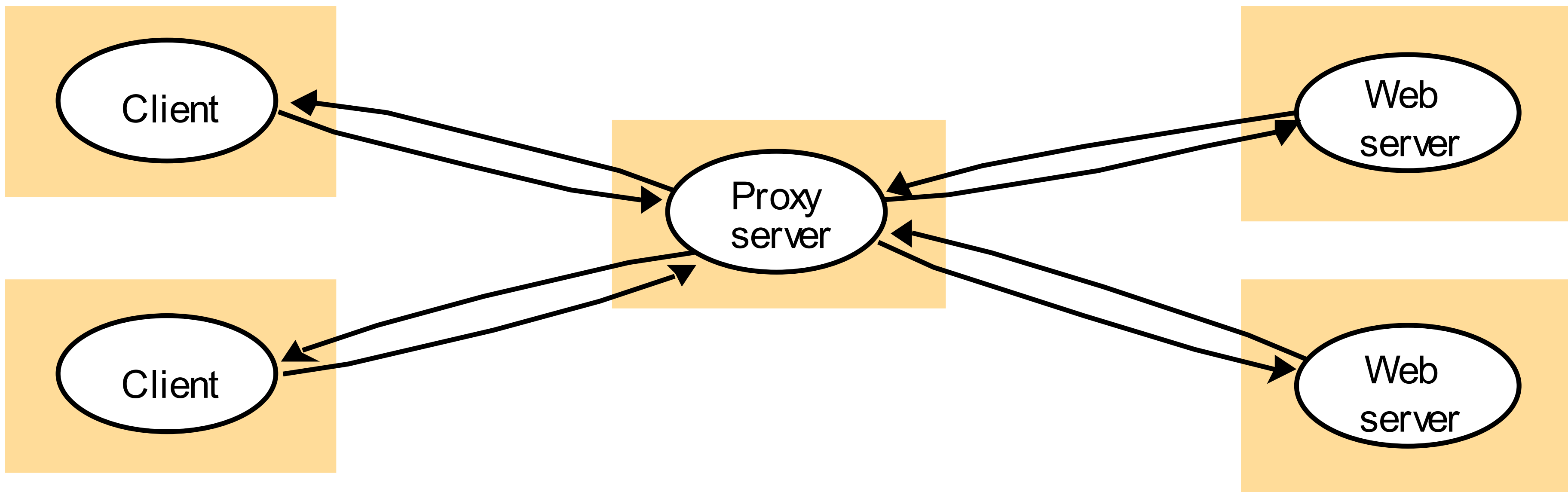
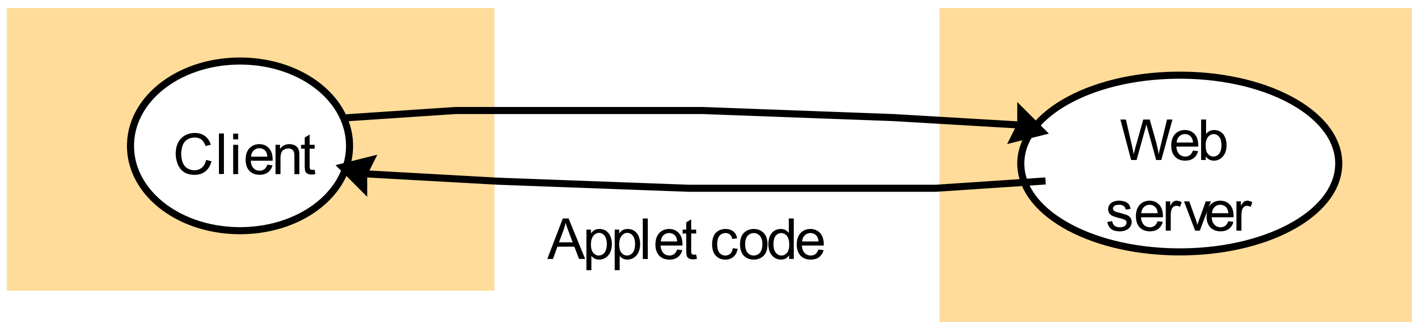


Figure 2.6
Web applets

a) client request results in the downloading of applet code



b) client interacts with the applet

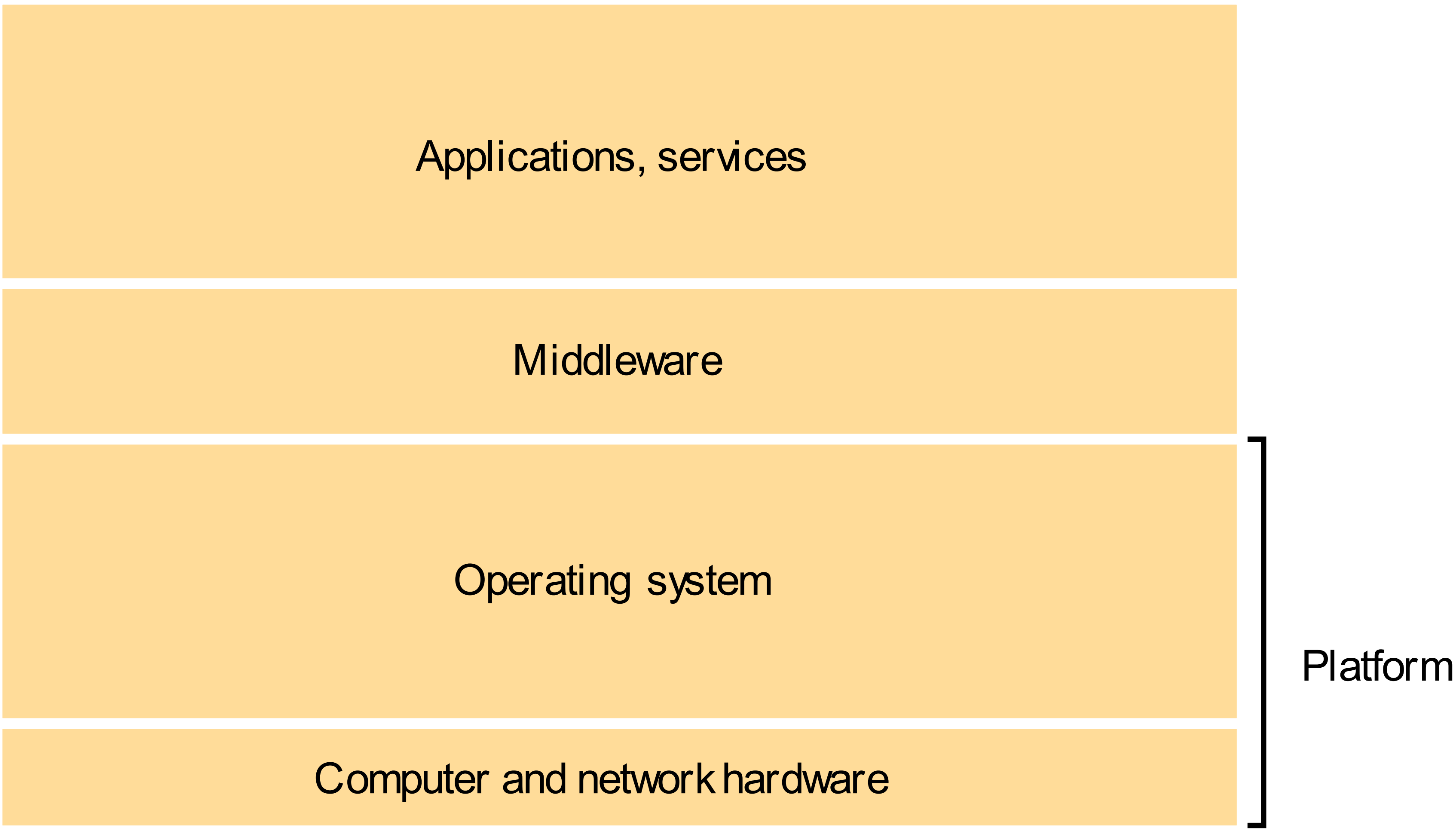
Architectural Patterns [2.3.2]

- Build on more primitive architectural elements in [2.3.1] and before
- “not themselves necessarily complete solutions but rather offer partial insights that, when combined with other patterns, lead the designer to a solution for a given problem domain”.
  - Extremely nice definition, lots of issues behind it!
- Patterns we cover
  - Layering
  - Tiered architectures
  - Thin clients
  - Other misc: proxy, brokerages, reflection

Layering

- Familiar from networking design
- In a DS, means a vertical organization of services into service layers
- **Platform**: lowest-level HW and SW layers
- **Middleware**: layer(s) of software above platform
  - masking heterogeneities
  - Providing higher-level programming abstraction
    - much closer to application's items of domains than the platform
  - Supports different kinds of interactions: RCP, RMI, pub-sub, …

Figure 2.7
Software and hardware service layers in distributed systems

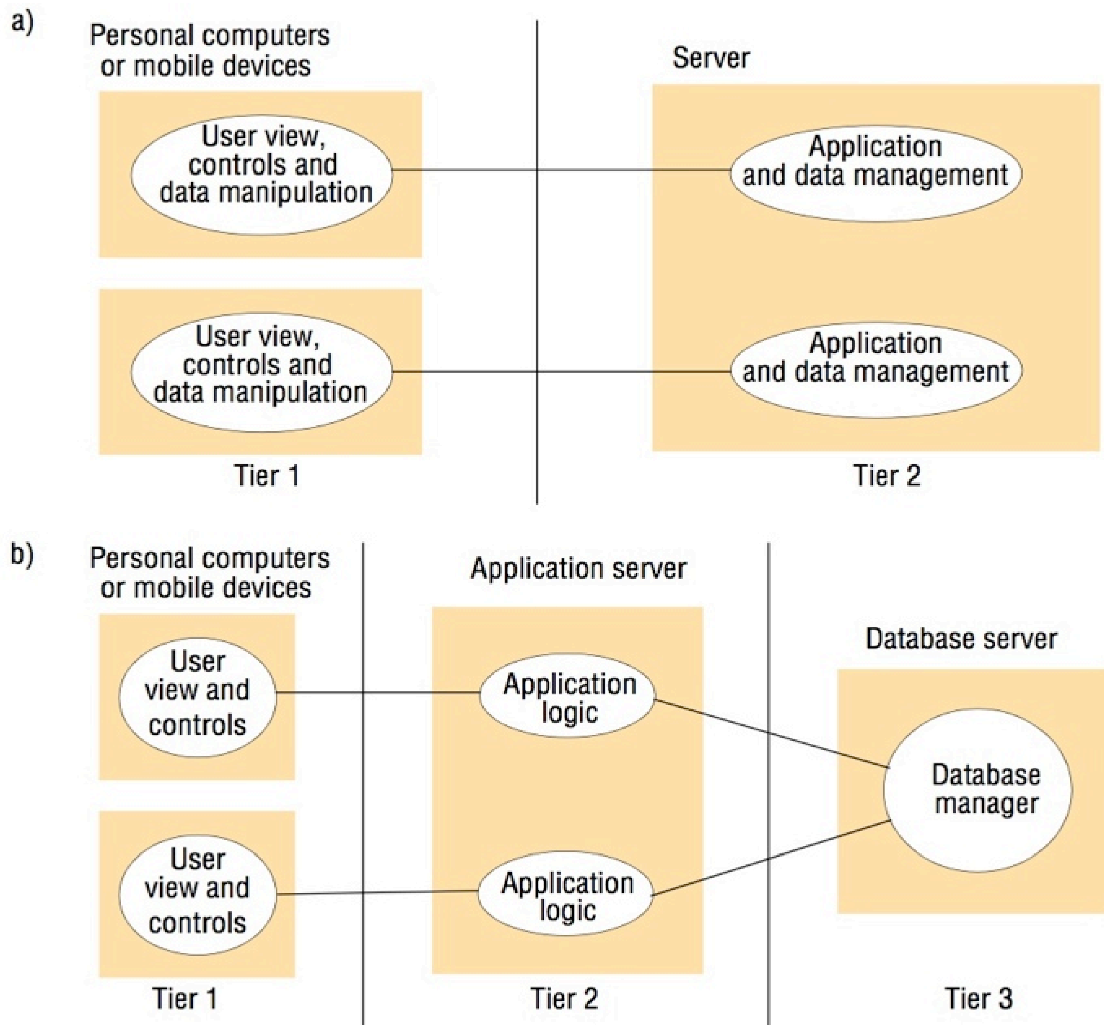


Note: some would consider the Platform to also include Middleware

Tiered Architectures

- Horizontal organization of application/service functionality across different servers
- Typical **three-tiered architecture**:
  - **Presentation logic**: user interactions and visualization
  - **Application logic**: app-specific processing (AKA **business logic**)
  - **Data logic**: persistent storage of data (e.g., database)
  - Above on separate processes
- Two-tiered can split above functionality across client-server in different ways
- (Read about AJAX, testable but not lecturing on)
- Q: tiered architectures contradictory or complimentary to layering?

Figure 2.8
Two-tier and three-tier architectures



Thin Clients & Other Patterns

- General-purpose desktop computer can be a pain to manage
- **Thin client**: SW layer supporting a window-based UI accessing remote programs and servers
- X-Windows early example
- Other architectural patterns
  - **Proxy**: intermediate in local address space (MW, web proxies)
  - **Brokerage**: **service broker** helps **service requester** find the right **service provider**
  - **Reflection**: applicaition/service utilizes knowledge of its internal structure; very very useful (Blair research)
    - **Introspection**: dynamic discovery of properties (read-only)
    - **Intercession**: dynamically modifying structure or behavior

Figure 2.10
Thin clients and compute servers

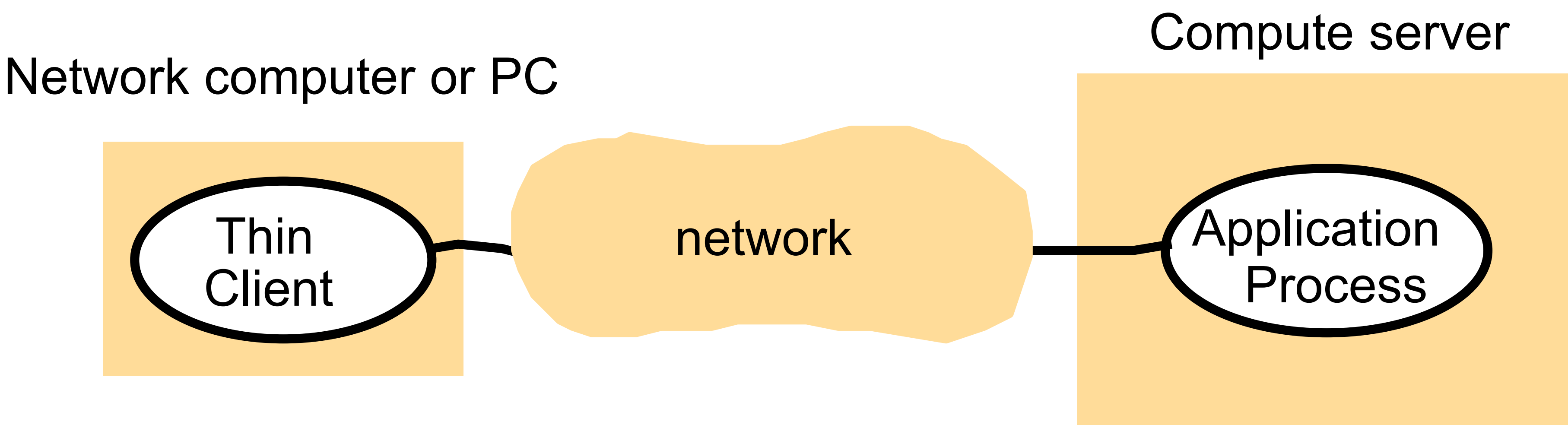
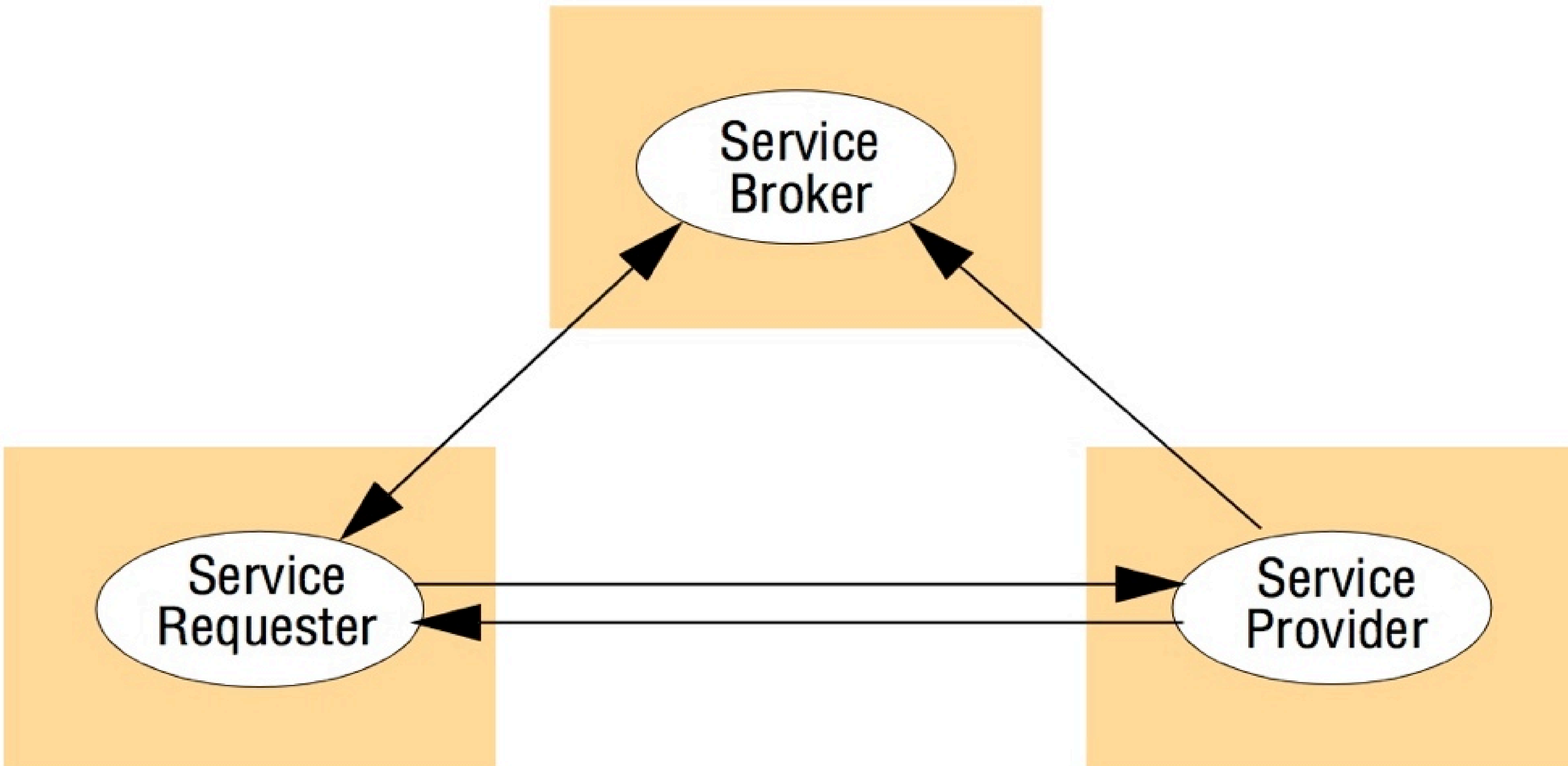


Figure 2.11
The web service architectural pattern



Associated Middleware Solutions [2.3.3]

- Categories: RPC, group communication, client-server, publish-subscribe, …..
- Limitations of middleware
  - Sometimes need application-specific knowledge for performance and reliability reasons
    - E.g., reliable email delivery on top of TCP/IP
  - Classic paper: end-to-end argument in system design [Saltzer et al 1984]: **required for 564 AND 464**
    - Some comms-related functions can only be done right with app knowledge
    - So don't push those functions into the comms layer
  - Authors consider this a limitation of MW, I consider it an opportunity for MW (and good research done on it, e.g., DARPA Quorum …)
    - QoS-enabled, adaptive MW can really help here (BBN QuO)

Figure 2.12
Categories of middleware (some overlap, more in Chap 8)

Major categories:	*Subcategory*	*Example systems*
Distributed objects (Chapters 5, 8)	Standard	RM-ODP
	Platform	CORBA
	Platform	Java RMI
Distributed components (Chapter 8)	Lightweight components	Fractal
	Lightweight components	OpenCOM
	Application servers	SUN EJB
	Application servers	CORBA Component Model
	Application servers	JBoss
Publish-subscribe systems (Chapter 6)	-	CORBA Event Service
	-	Scribe
	-	JMS
Message queues (Chapter 6)	-	Websphere MQ
	-	JMS
Web services (Chapter 9)	Web services	Apache Axis
	Grid services	The Globus Toolkit
Peer-to-peer (Chapter 10)	Routing overlays	Pastry
	Routing overlays	Tapestry
	Application-specific	Squirrel
	Application-specific	OceanStore
	Application-specific	Ivy
	Application-specific	Gnutella

Fundamental Models [2.4]

- Above arch. models all share some fundamental properties!
- **<u>Fundamental models</u>**: contain only essential details to reason about some aspect of system's behavior
- Purpose
  - Make explicit all relevant assumptions
  - Make generalizations about what is possible or impossible, given assumptions
- Fundamental models studied here [2.4.x]
  1. Interaction model: what kind of information (message) flow
  2. Failure model: in what ways we assume components can fail
  3. Security model: what kinds of attacks may we suffer, and what can be done about them?

Interaction model [2.4.1]

- Processes composed in many ways in arch. models!
- **Distributed algorithm**: steps distributed components take, including message sending/receiving
  - Cannot often predict rate and timing of messages. Why?
- Performance of communications channels
  - Latency
  - Bandwidth
  - Jitter
- Computer clocks and timing events
  - Internal clocks can REALLY drift on unmanaged machines (2003 blackout post-mortem)
  - GPS helps, but not a panacea

Synchronous and Asynchronous DSs

- **Synchronous DS**: known (lower and upper) bounds on
  - Time to execute each step in a distributed algorithm
  - Message transmission time
  - Clock drift rate
- **Asynchronous DS**: no bounds above known. (impacts?)
- Technique (here and for failures): transform Asynch. DS into Synch. DS plus assumed failures (timeouts!)
- Q: concrete examples of both kinds, in practice?
- Q: causes of asynch. Behavior?
- Note: synch/asynch DS vs. invocation

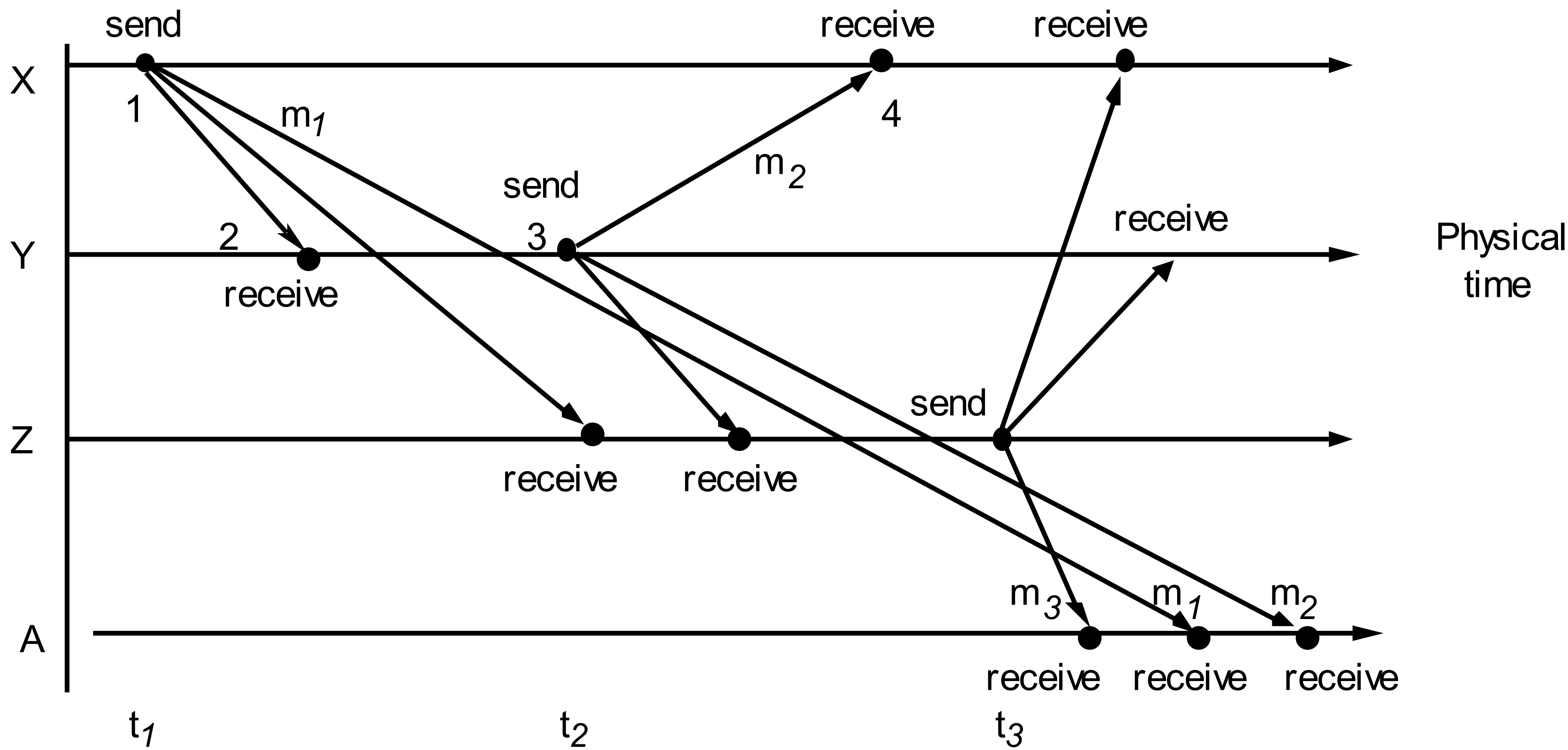
Agreement in Pepperland

- Famous “Byzantine Generals” problem from 1982
- Two divisions of Pepperland Army (Apple, Orange) camped atop two hills with enemy (Blue Meanies) inbetween
  - If attack, successful if both attack at once, one attacker dies
  - Safe if stay in camp (0 attack)
  - Need to both decide same thing: who leads, and when
- Distributed agreement: agreeing on a common decision
  - Can still do under some circumstances with asynch. DS
  - E.g., divisions both send other #soldiers left, one with most leads (tiebreaker predefined)
  - But in an Asynch. Pepperland can’t decide when to charge safely
  - Synch. Pepperland, can agree to charge after max delivery time

Event ordering (Chapter 14)

- Often very useful to describe system in terms of message passing
- Key issue: MsgA before MsgB, concurrent, or after?
- Problem:
  - clocks not accurate enough to tell, but order can affect what we need to do!
  - Messages can be delivered to app in different orders (Fig 2.13)
  - E.g. email (or netnews) reply display problem
- Logical time: builds basis to reason about events
  - Based on message receive and send events
  - E.g., in global (logical) time, send(msg) < recv(msg)
  - Event orderings transitive

Figure 2.13
Real-time ordering of events



Failure model [2.4.2]

- Nice textbook: spread throughout book systematically…
- **Omission failure**: component (process or comm. channel) fails to do what supposed to do
  - Can bound degree of omission (e.g., ≤3 consecutive omissions)
  - Crash failure: fails "cleanly": no errors
  - Omission failure: fails "cleanly" but not necessarily permanently
  - Fail-Stop failure: fails "cleanly" and detectably (Schlichting ~1983)
  - Can have above happen with either process or comm. channel
- **Arbitrary failure**: can do anything (including omission, …)
  - Send wrong value (worst possible for algorithm) or lie about ID
    - Lie about what received from others in a step
    - **Two-faced behavior**: tell different processes different "decision"
  - Send bad syntax
- **Timing failure**: do something later (or earlier!) than should

Figure 2.15
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 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.
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 2.16
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.

Masking failures

- Can build a reliable DS from unreliable components!
  - Have to make failure assumptions and build on them
- Service can mask a failure (hide it from other components)
  - Hide it (e.g., replicated servers)
  - Convert to easier type to deal with: checksums convert arbitrary failure to omission failure
  - A failure detection service can convert crash failures into fail-stop ones.
  - Temporal redundancy can mask an omission failure (with bounded degree) of the communications channel

Failure detection in Pepperland

- Failure detection: assume Blue Meanies could defeat either Pepperland division while encamped
  - I.e., either division can fail (to exist!)
  - Assume if alive, division sends “heartbeat” messages regularly
- Asynch. DS: neither Pepperland division can tell if other defeated or messengers slow
- Synch DS: can tell
  - But division may be defeated after last messenger

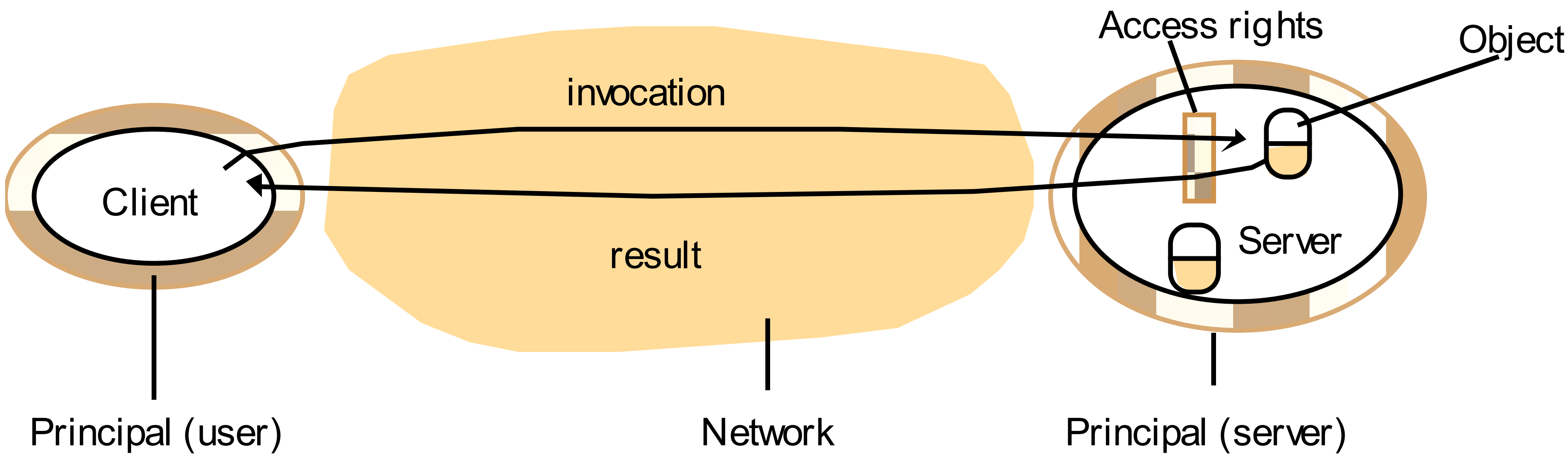
Agreement in Pepperland

- What if messenger delivery unbounded: asynch. comms.
  - Pepperland divisions can’t decide to both either charge or surrender
  - I.e., can’t both agree, may get incorrect agreement
  - E.g, if last message does not get there, can we live without it?
  - Second to last then?
  - …
- Bottom line: in asynch. DS, in presence of even one comm. Failure, cannot guarantee agreement will be reached
  - Very fundamental result in DC
  - Fischer, Lynch, and Patterson 1985 (called “FLP85”)
  - E.g., Bakken’s Razor derivation uses this

Security Model [2.4.3]

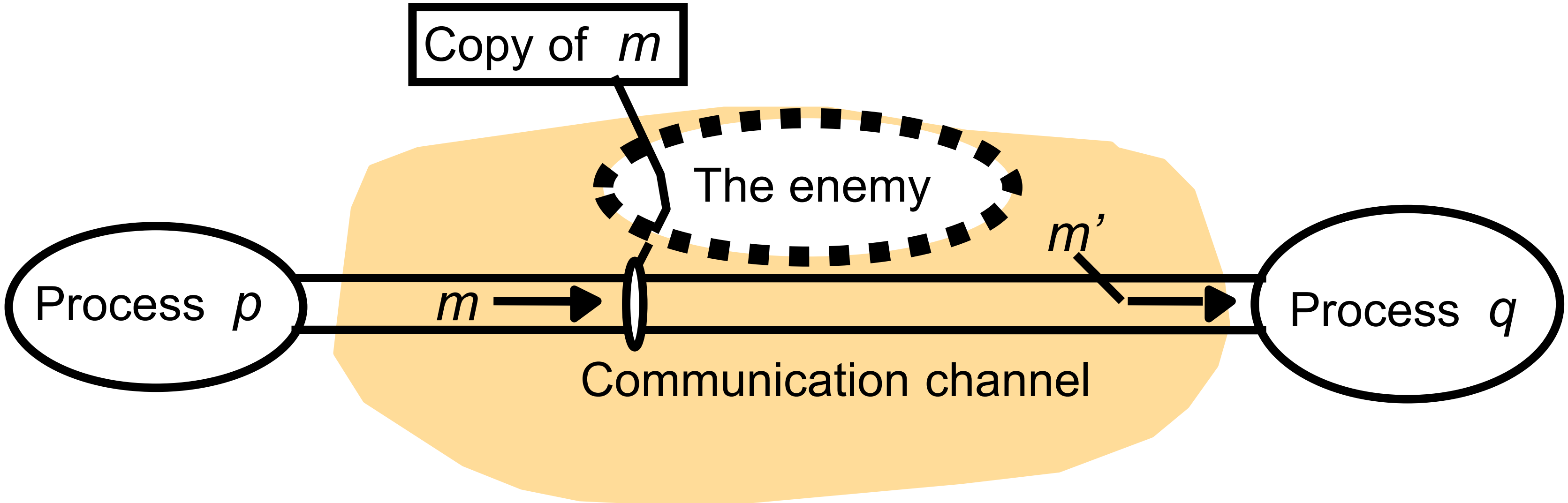
- It's a nasty world out there!

Figure 2.17
Objects and principals



- Server manages collection of objects
- Principal, access rights

Figure 2.18
The enemy (modeling security threats)

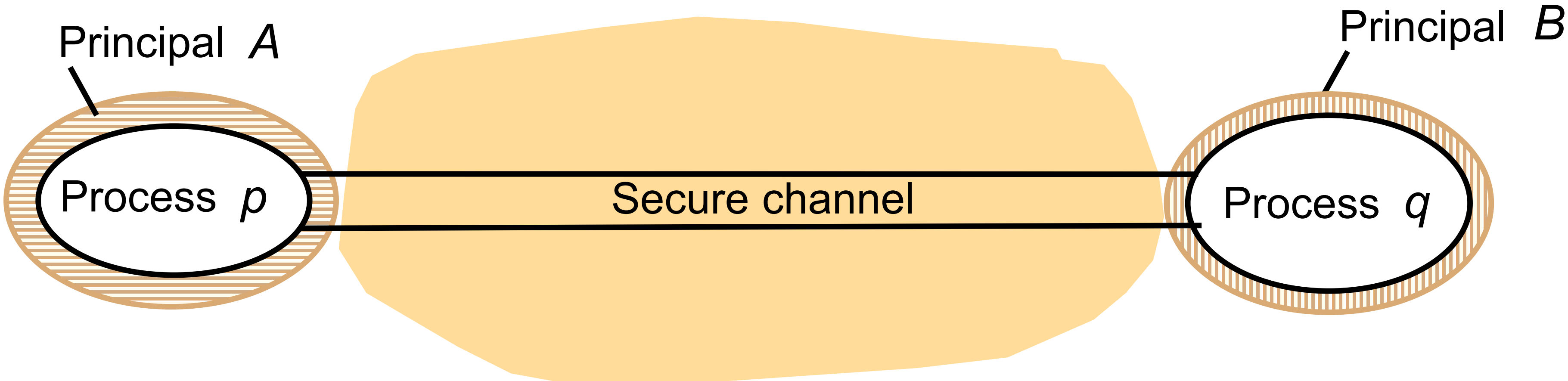


- Server can't always know principal of message sender
- Client can't always know principal of sender of reply
- Comms channels: can copy, alter, inject, replay msgs
  - Can defeat with abstraction of secure channel

Defeating security threats

- Cryptography
- Shared secrets
- Authentication
- Secure channels (Fig 2.19)
- Other possible threats from an enemy
  - Denial of Service
  - Mobile code
- Uses of Security models
  - Not just straightforward use of access control etc!
  - “If you think encryption is the solution to your problem, then you don’t understand encryption, and you don’t understand your problem.” Needham or Lampson

Figure 2.19
Secure channels



- Each process reliably knows other principal
- Channel provides privacy and integrity
- Message has physical or logical timestamp to prevent replay or reordering of messages