System Design and Software Architecture

Introduction into Software Engineering
Lecture 11

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Where are we?

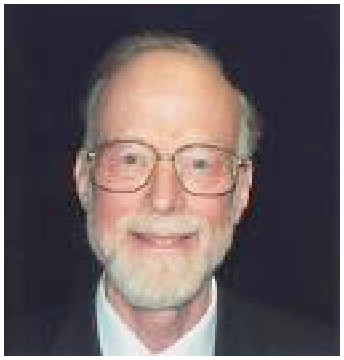
- We have covered Ch 1 - 4 and Ch 7
- We are moving “back” to Chapter 5 and 6.

Announcements

- Mid-term exam:
- Date, Time and Location:
  - 2nd June 2007, 13:00-14:30, MW 0001
- Programming assignments in exercises will start next week
  - Please bring your laptop to the exercise sessions
  - Please visit website and install prerequisites.

Design is Difficult

- There are two ways of constructing a software design (Tony Hoare):
  - One way is to make it so simple that there are obviously no deficiencies
  - The other way is to make it so complicated that there are no obvious deficiencies."
- Corollary (Jostein Gaarder):
  - If our brain would be so simple that we can understand it, we would be too stupid to understand it.



Sir **Antony Hoare,** *1934
- Quicksort
- Hoare logic for verification
- CSP (Communicating Sequential Processes): modeling language for concurrent processes (basis for Occam).

Jostein Gardner, *1952, writer
Uses metafiction in his stories:
Fiction which uses the device of fiction
- Best known for: „Sophie‘s World“.

Why is Design so Difficult?

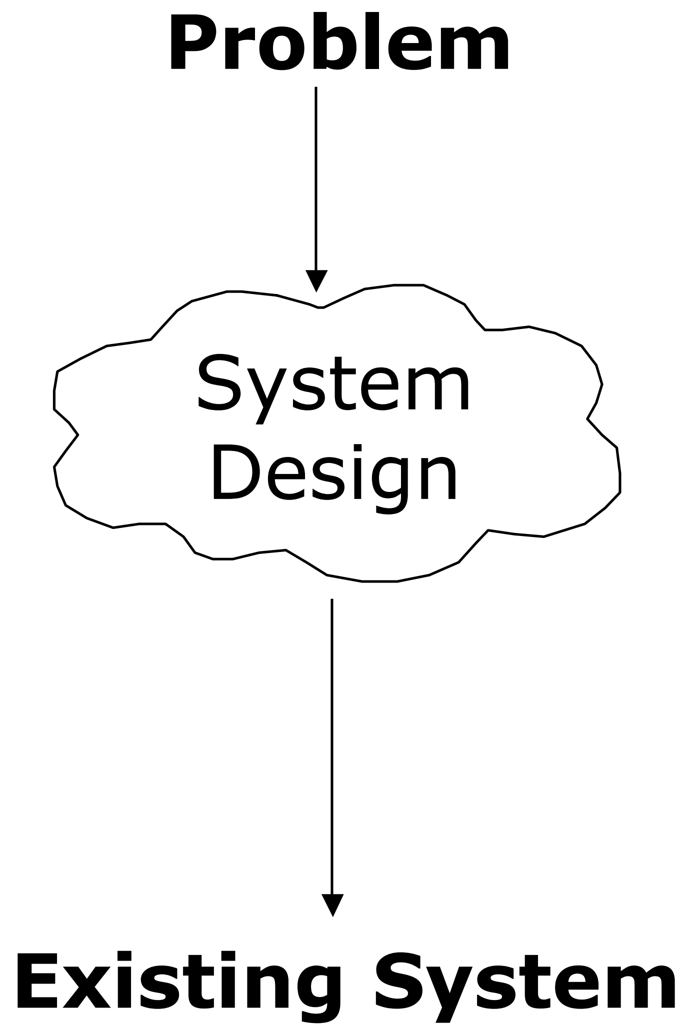
- Analysis: Focuses on the application domain
- Design: Focuses on the solution domain
  - The solution domain is changing very rapidly
    - Halftime knowledge in software engineering: About 3-5 years
    - Cost of hardware rapidly sinking
  - ➢ Design knowledge is a moving target

- Design window: Time in which design decisions have to be made.

The Scope of System Design

- Bridge the gap
  - between a problem and an existing system in a manageable way

- How?
- Use Divide & Conquer:
  1) Identify design goals
  2) Model the new system design as a set of subsystems
  3-8) Address the major design goals.



System Design: Eight Issues

System Design

1. Identify Design Goals
- Additional NFRs
- Trade-offs

2. Subsystem Decomposition
- Layers vs Partitions
- Coherence & Coupling

3. Identify Concurrency
- Identification of Parallelism (Processes, Threads)

4. Hardware/ Software Mapping
- Identification of Nodes
- Special Purpose Systems
- Buy vs Build
- Network Connectivity

5. Persistent Data Management
- Storing Persistent Objects
- Filesystem vs Database

6. Global Resource Handlung
- Access Control
- ACL vs Capabilities
- Security

7. Software Control
- Monolithic
- Event-Driven
- Conc. Processes

8. Boundary Conditions
- Initialization
- Termination
- Failure.

Overview

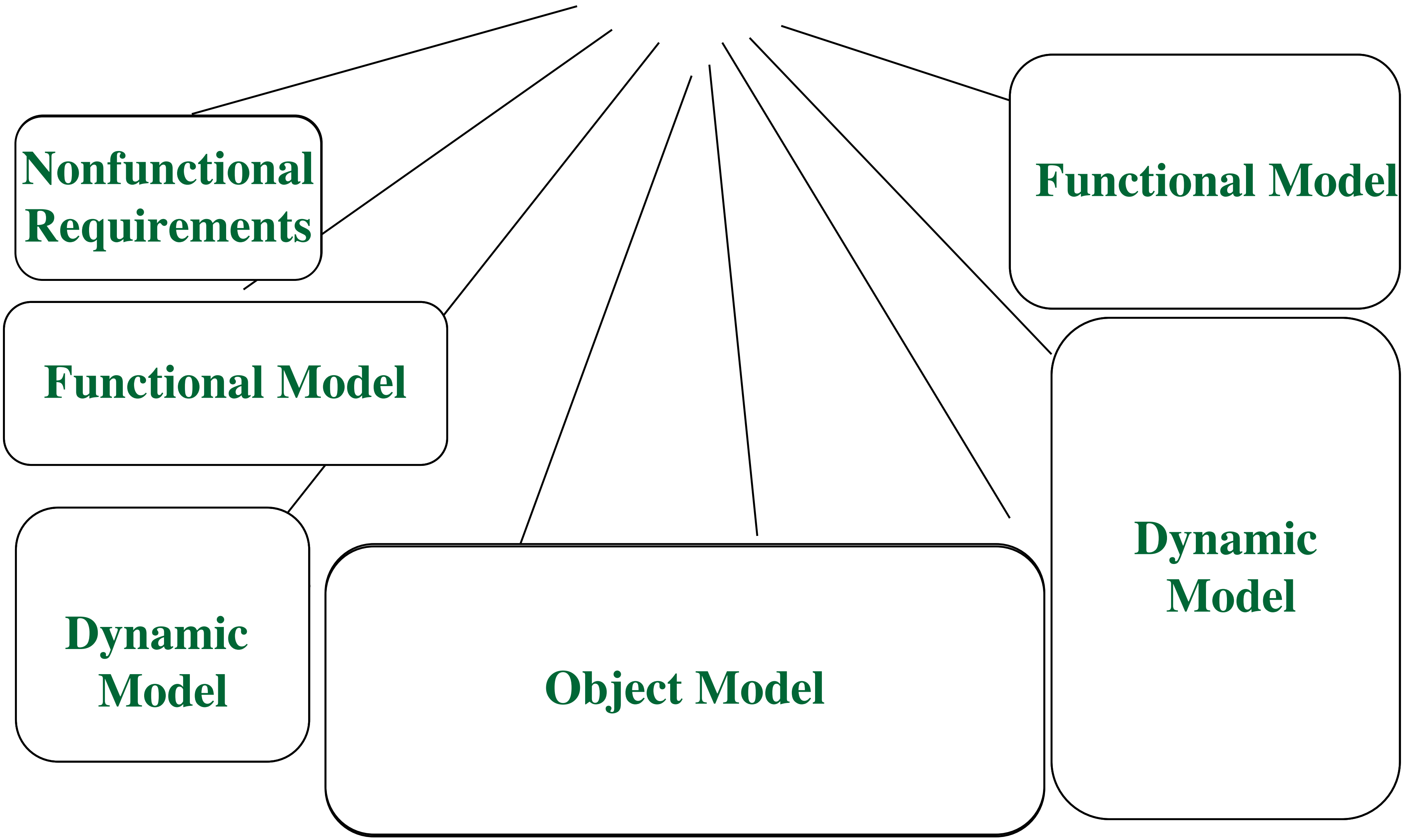
System Design I (This Lecture)

0. Overview of System Design
1. Design Goals
2. Subsystem Decomposition, Software Architecture

System Design II (Next Lecture)

3. Concurrency: Identification of parallelism
4. Hardware/Software Mapping:
   Mapping subsystems to processors
5. Persistent Data Management: Storage for entity objects
6. Global Resource Handling & Access Control:
   Who can access what?)
7. Software Control: Who is in control?
8. Boundary Conditions: Administrative use cases.

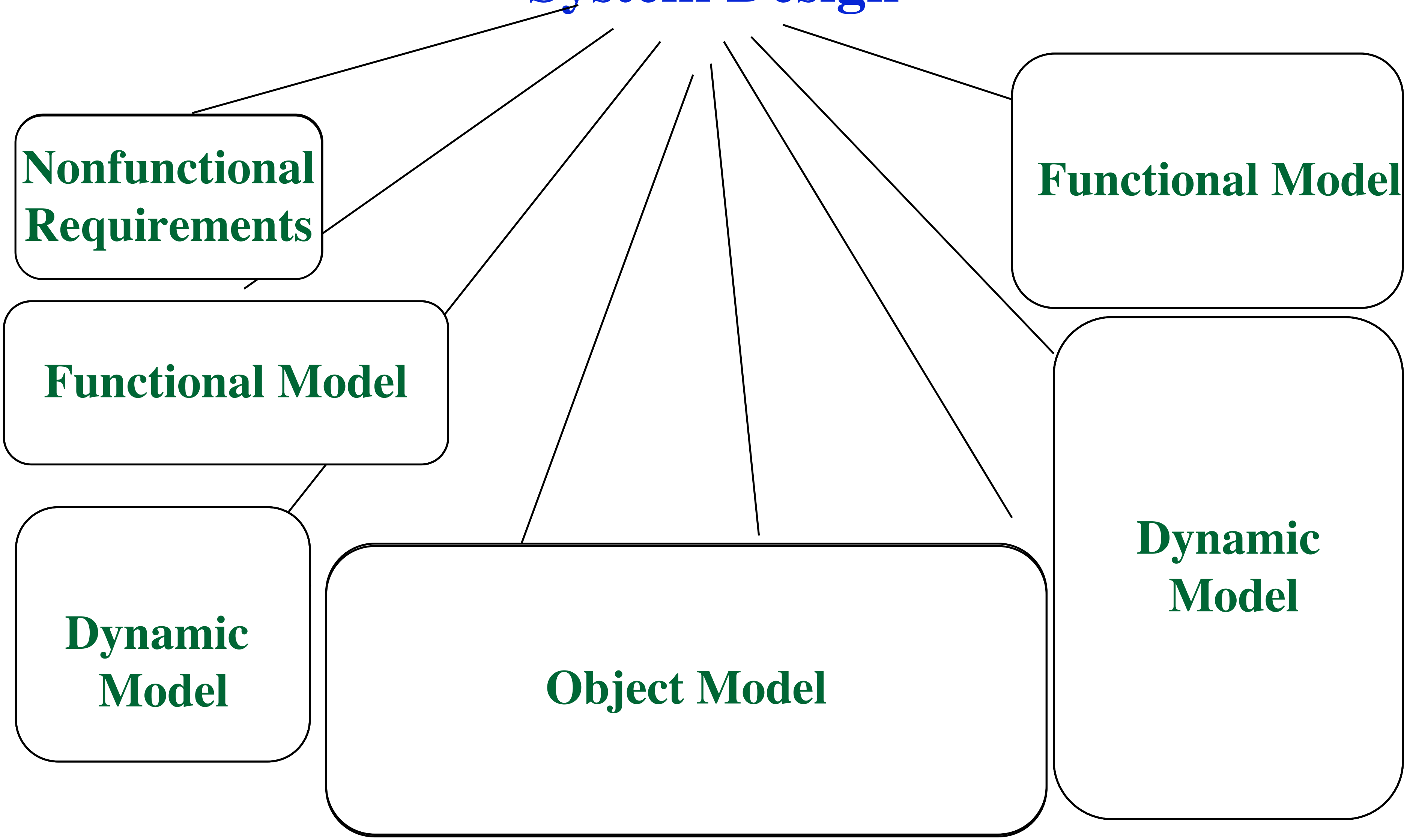
Analysis: Requirements and System Model



How the Analysis Models influence System Design

- Nonfunctional Requirements
  => Definition of Design Goals
- Functional model
  => Subsystem Decomposition
- Object model
  => Hardware/Software Mapping, Persistent Data Management
- Dynamic model
  => Identification of Concurrency, Global Resource Handling, Software Control
- Finally: Hardware/Software Mapping
  => Boundary conditions

From Analysis to System Design

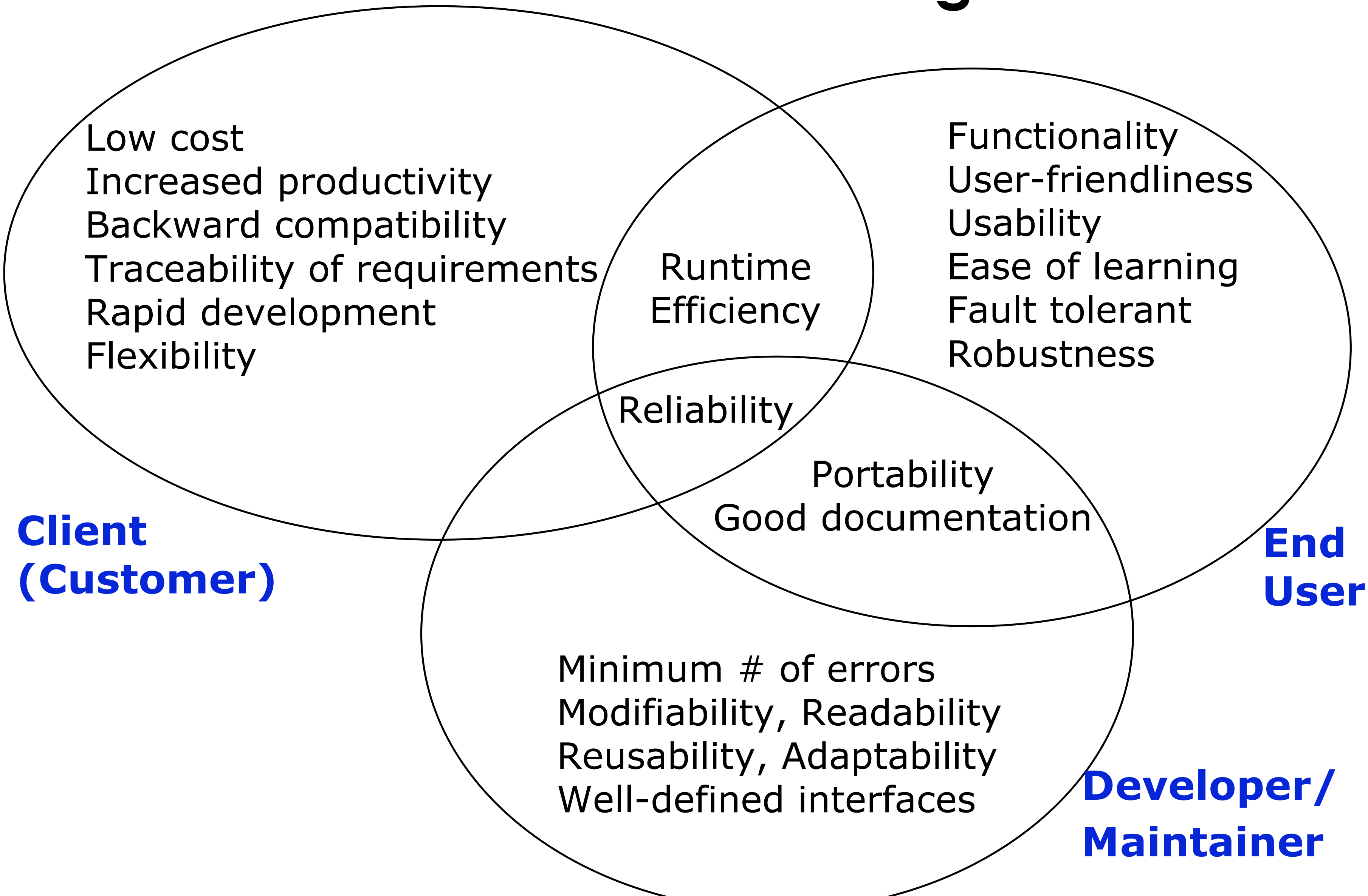


Example of Design Goals

- Reliability
- Modifiability
- Maintainability
- Understandability
- Adaptability
- Reusability
- Efficiency
- Portability
- Traceability of requirements
- Fault tolerance
- Backward-compatibility
- Cost-effectiveness
- Robustness
- High-performance

- Good documentation
- Well-defined interfaces
- User-friendliness
- Reuse of components
- Rapid development
- Minimum number of errors
- Readability
- Ease of learning
- Ease of remembering
- Ease of use
- Increased productivity
- Low-cost
- Flexibility

Stakeholders have different Design Goals



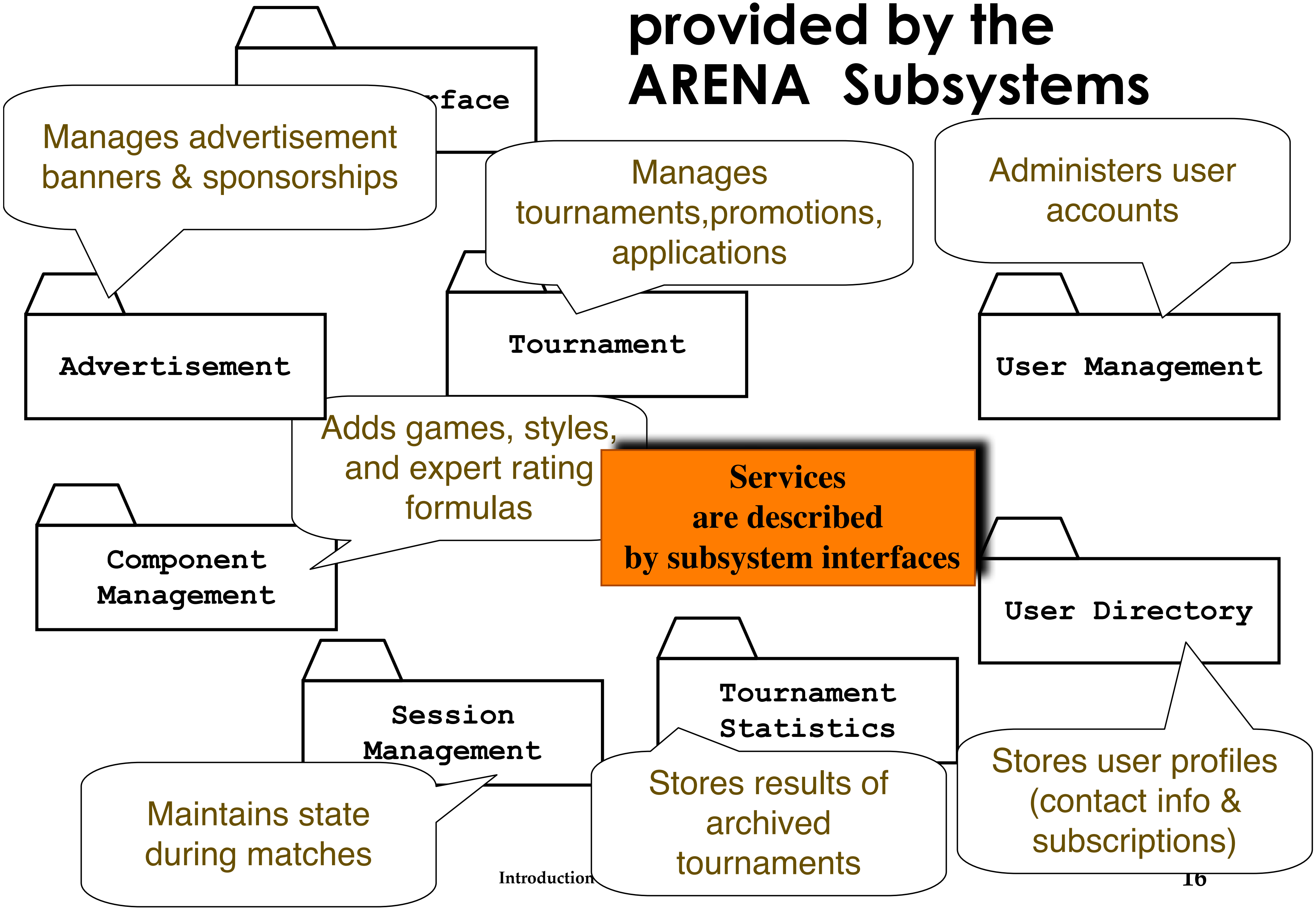
Typical Design Trade-offs

- Functionality v. Usability
- Cost v. Robustness
- Efficiency v. Portability
- Rapid development v. Functionality
- Cost v. Reusability
- Backward Compatibility v. Readability

Subsystem Decomposition

- Subsystem
  - Collection of classes, associations, operations, events and constraints that are closely interrelated with each other
  - The objects and classes from the object model are the "seeds" for the subsystems
  - In UML subsystems are modeled as packages
- Service
  - A set of named operations that share a common purpose
  - The origin ("seed") for services are the use cases from the functional model
- Services are defined during system design.

Example: Services provided by the ARENA Subsystems



Subsystem Interfaces vs API

- Subsystem interface: Set of fully typed UML operations
  - Specifies the interaction and information flow from and to subsystem boundaries, but not inside the subsystem
  - Refinement of service, should be well-defined and small
  - *Subsystem interfaces are defined during object design*
- Application programmer's interface (API)
  - The API is the specification of the subsystem interface in a specific programming language
  - APIs are defined during implementation
- The terms subsystem interface and API are often confused with each other
  - *The term API should not be used during system design and object design, but only during implementation.*

Example: Notification subsystem

- Service provided by Notification Subsystem
    - LookupChannel()
    - SubscribeToChannel()
    - SendNotice()
    - UnscubscribeFromChannel()
- Subsystem Interface of Notification Subsystem
  - Set of fully typed UML operations
    - Left as an Exercise
- API of Notification Subsystem
  - Implementation in Java
  - Left as an Exercise.

Subsystem Interface Object

- Good design: The subsystem interface object describes *all* the services of the subsystem interface

- Subsystem Interface Object
  - The set of public operations provided by a subsystem

Subsystem Interface Objects can be realized with the Façade pattern (=> lecture on design patterns).

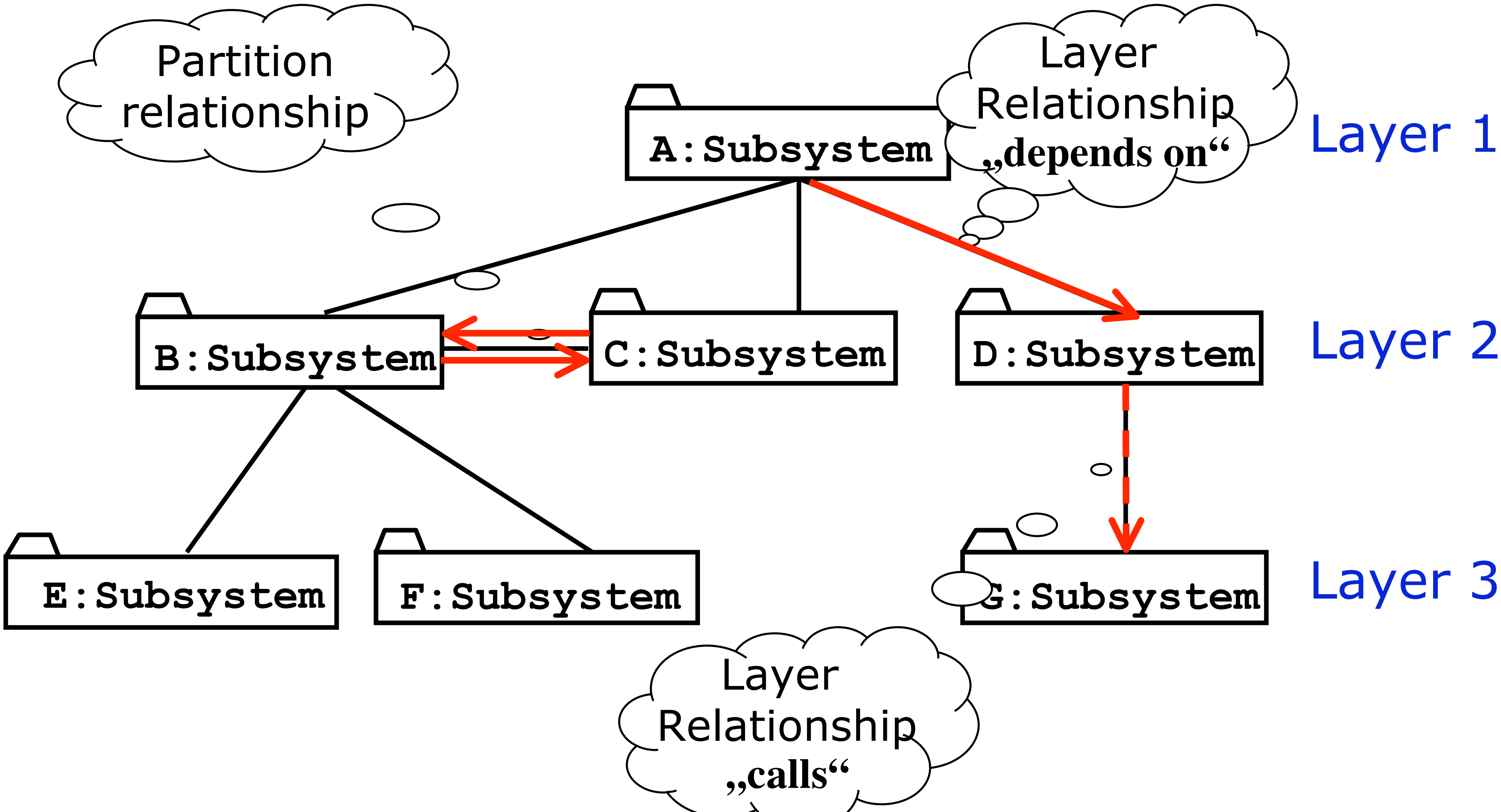
Properties of Subsystems: Layers and Partitions

- A layer is a subsystem that provides a service to another subsystem with the following restrictions:
  - A layer only depends on services from lower layers
  - A layer has no knowledge of higher layers
- A layer can be divided horizontally into several independent subsystems called partitions
  - Partitions provide services to other partitions on the same layer
  - Partitions are also called "weakly coupled" subsystems.

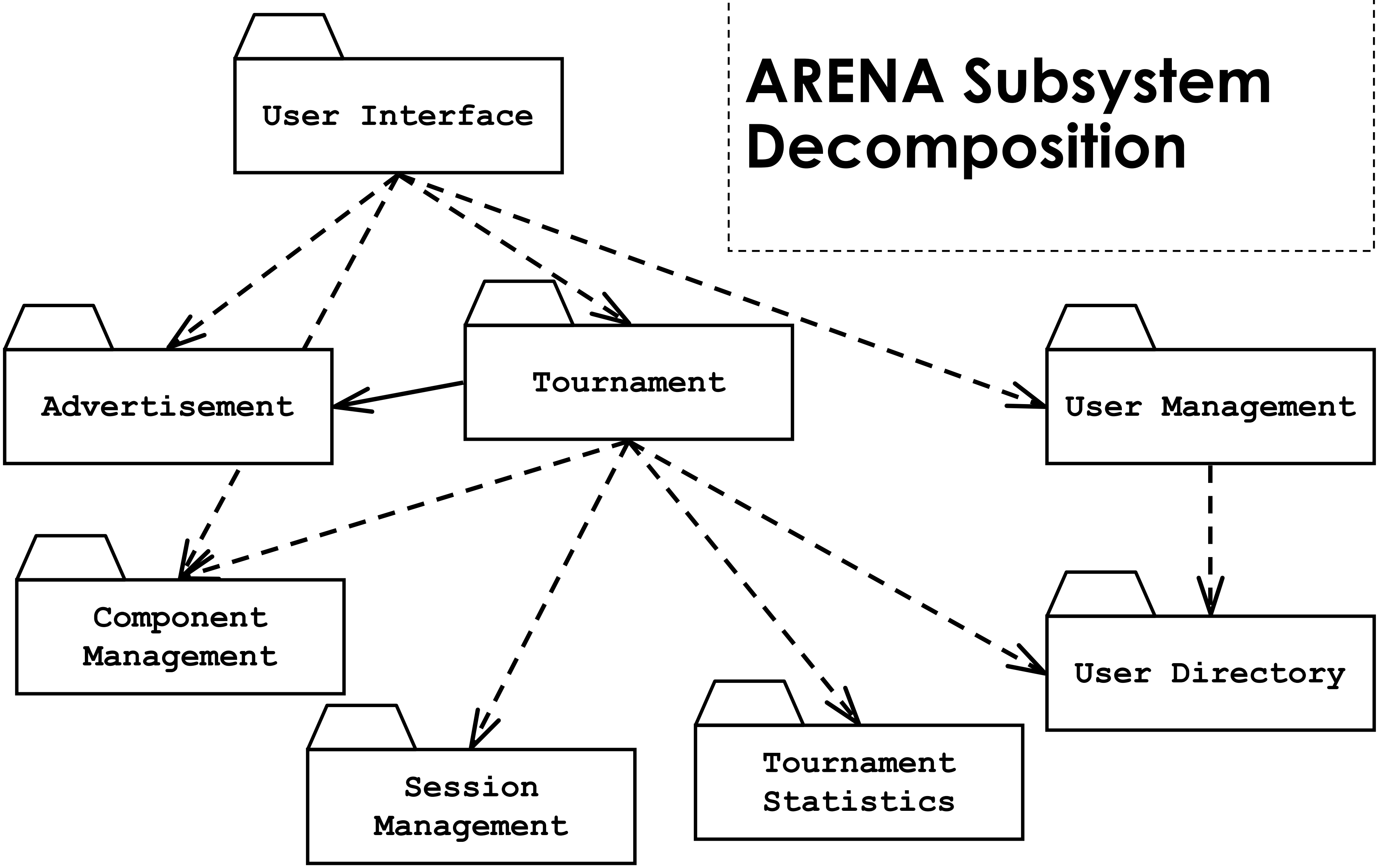
Relationships between Subsystems

- Two major types of Layer relationships
  - Layer A "depends on" Layer B (compile time dependency)
    - Example: Build dependencies (make, ant, maven)
  - Layer A "calls" Layer B (runtime dependency)
    - Example: A web browser calls a web server
    - Can the client and server layers run on the same machine?
      - Yes, they are layers, not processor nodes
      - Mapping of layers to processors is decided during the Software/hardware mapping!
- Partition relationship
  - The subsystems have mutual knowledge about each other
    - A calls services in B; B calls services in A (Peer-to-Peer)
- UML convention:
  - Runtime dependencies are associations with dashed lines
  - Compile time dependencies are associations with solid lines.

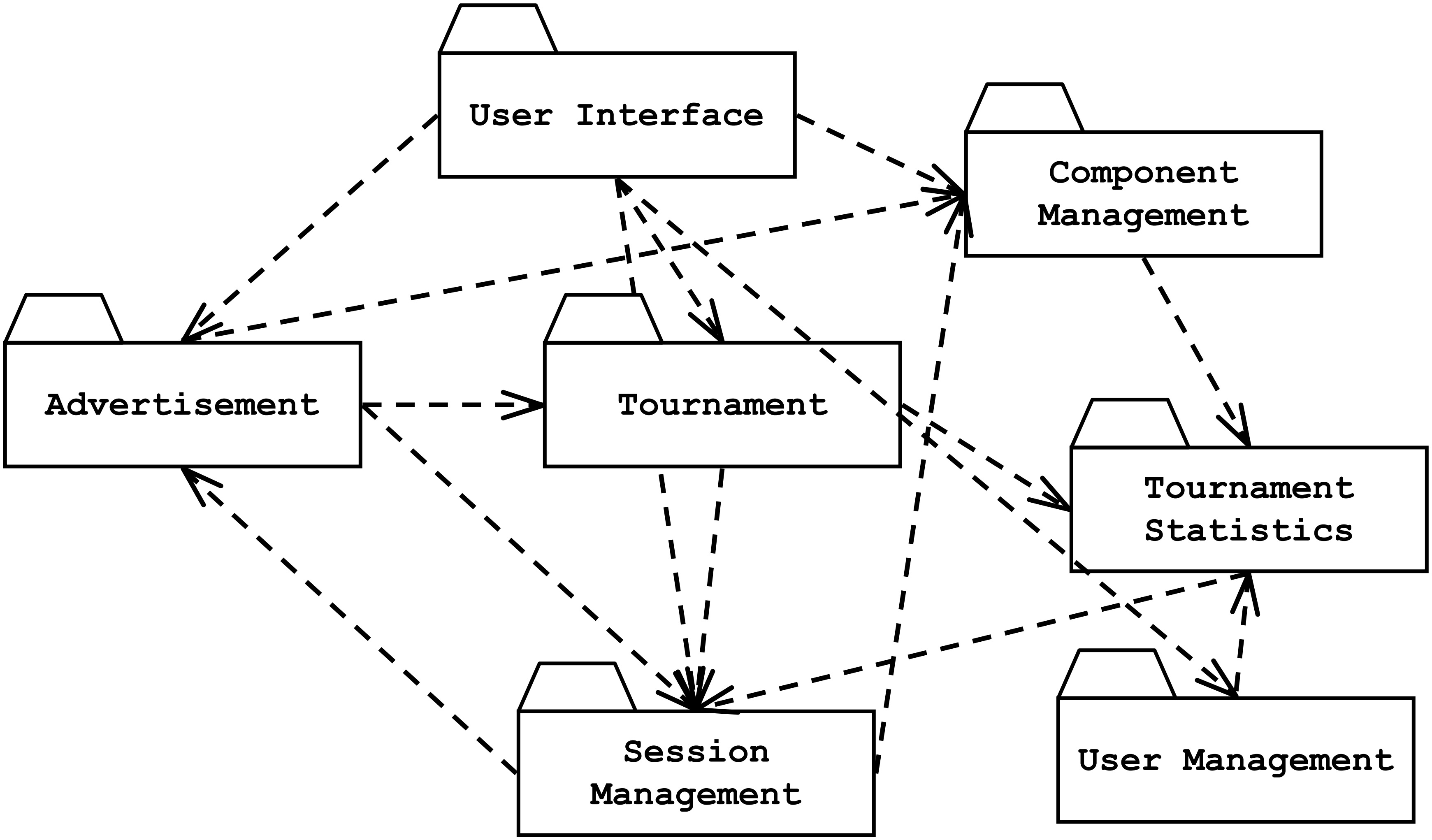
Example of a Subsystem Decomposition



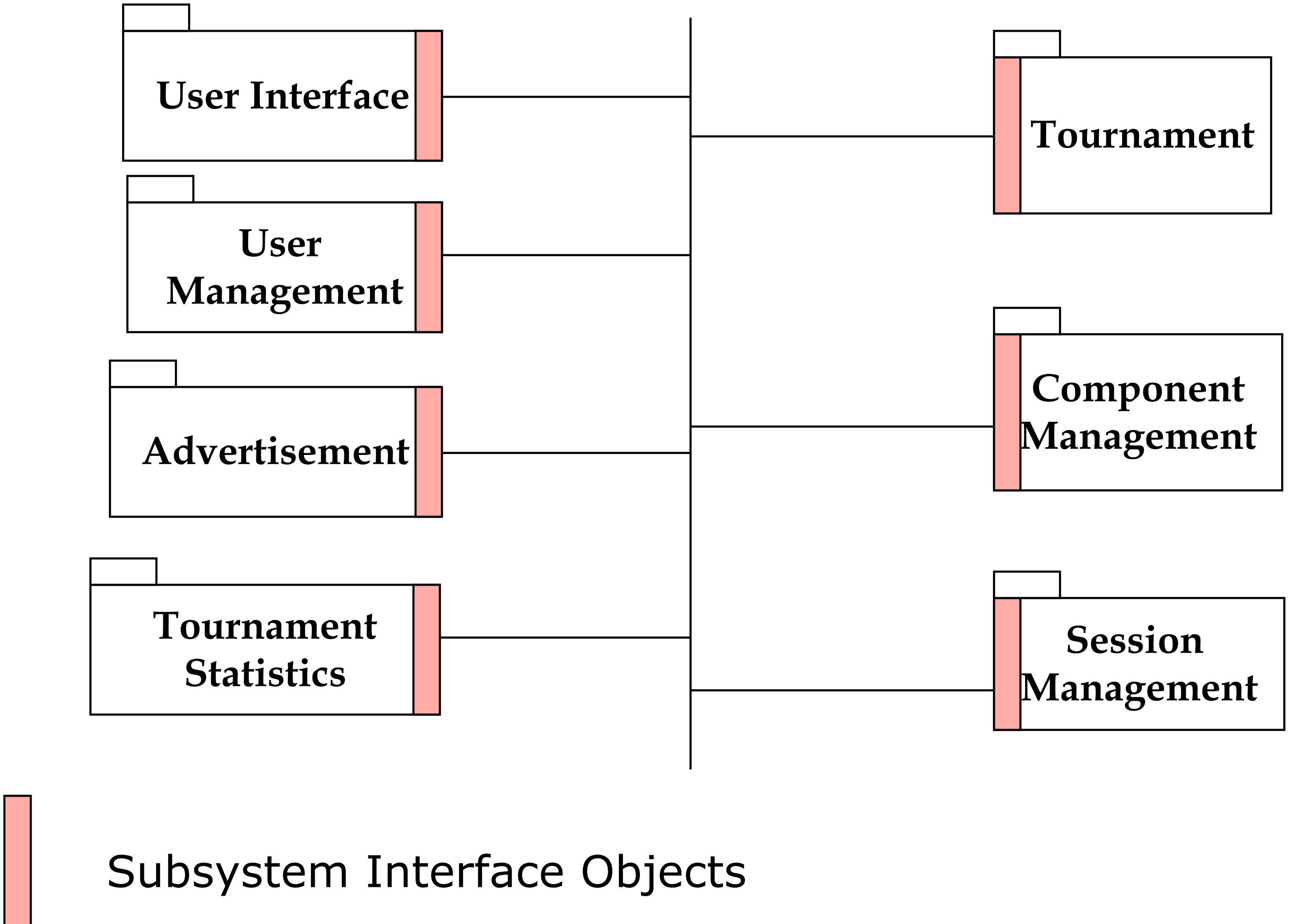
ARENA Subsystem Decomposition



Example of a Bad Subsystem Decomposition



Good Design: The System as set of Interface Objects



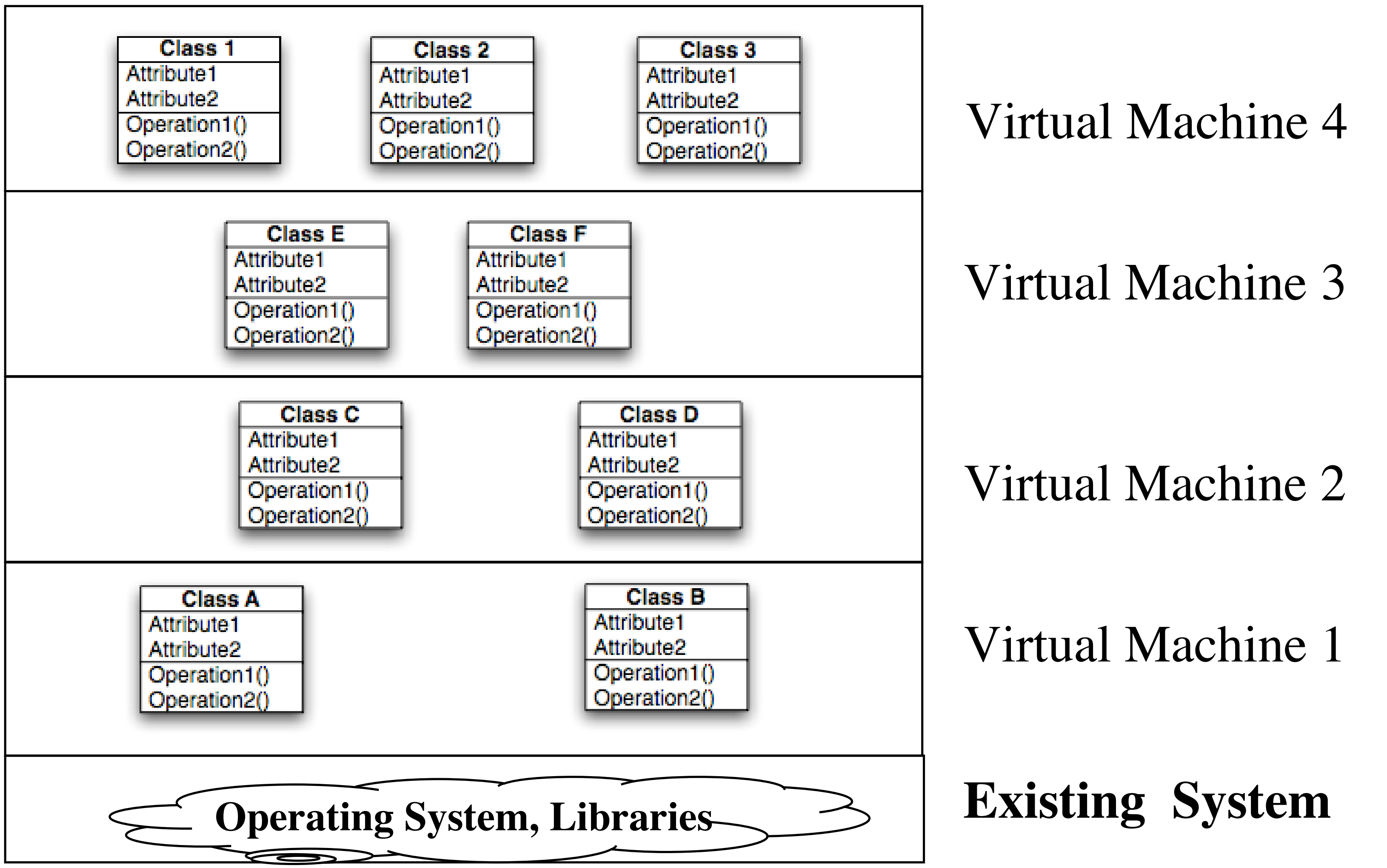
Subsystem Interface Objects

Virtual Machine

- The terms layer and virtual machine can be used interchangeably
  - Also sometimes called “level of abstraction”.
  - A virtual machine is an abstraction that provides a set of attributes and operations
- A virtual machine is a subsystem connected to higher and lower level virtual machines by "provides services for" associations.

Building Systems as a Set of Virtual Machines

A system is a hierarchy of virtual machines, each using language primitives offered by the lower machines.



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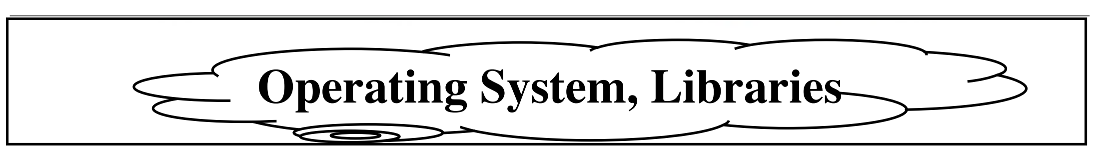
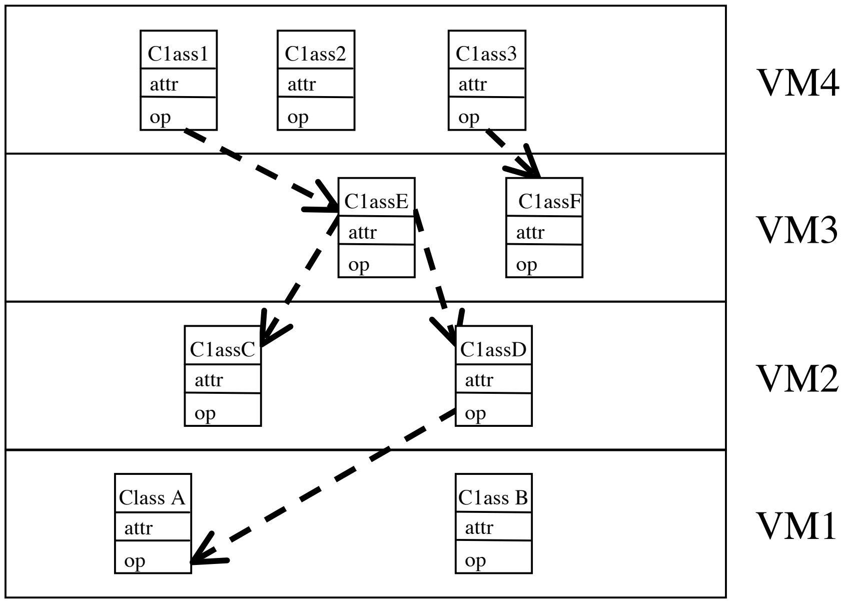


Existing System

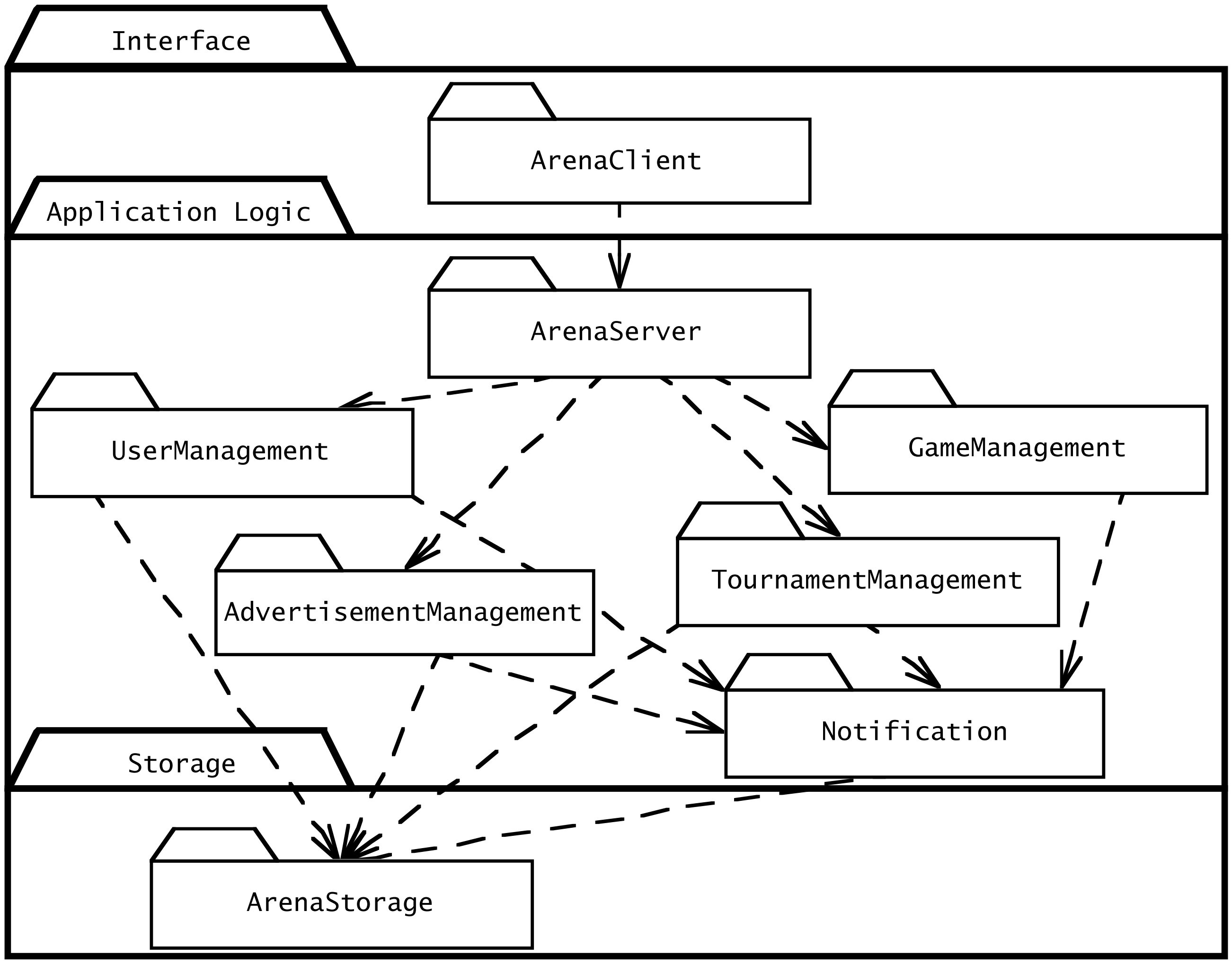
Closed Architecture (Opaque Layering)

- Each virtual machine can only call operations from the layer below

Design goals: Maintainability, flexibility.

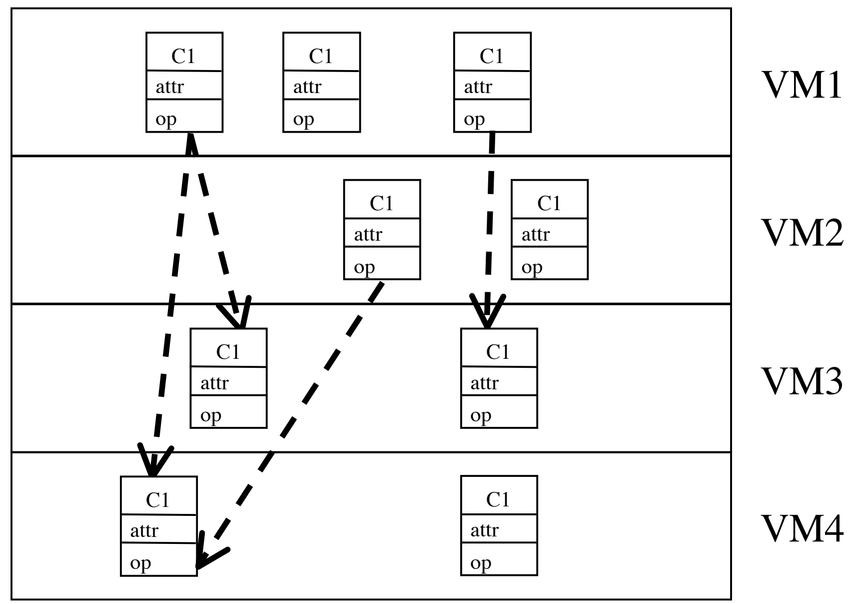


Opaque Layering in ARENA



Open Architecture (Transparent Layering)

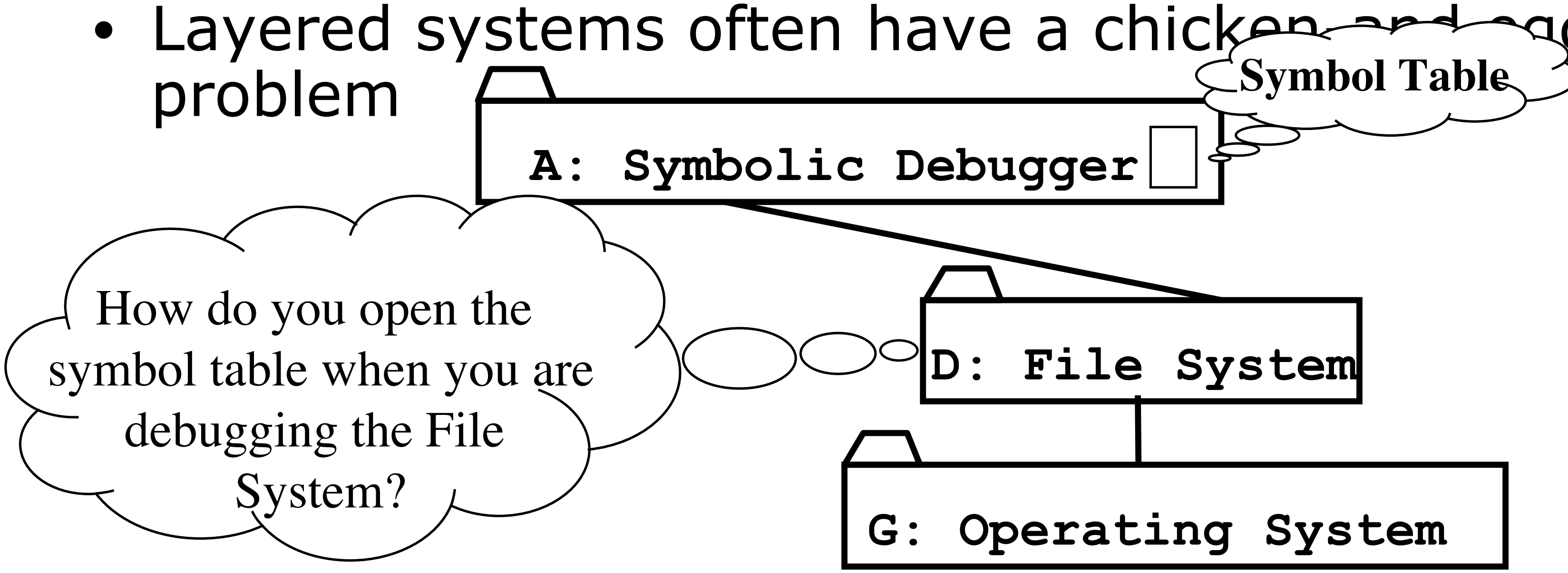
- Each virtual machine can call operations from any layer below



Design goal:
Runtime efficiency

Properties of Layered Systems

- Layered systems are hierarchical. This is a desirable design, because hierarchy reduces complexity
  - low coupling
- Closed architectures are more portable
- Open architectures are more efficient
- Layered systems often have a chicken and egg problem



Coupling and Coherence of Subsystems

- Goal: Reduce system complexity while allowing change
- Coherence measures dependency among classes
  - High coherence: The classes in the subsystem perform similar tasks and are related to each other via many associations
  - Low coherence: Lots of miscellaneous and auxiliary classes, almost no associations
- Coupling measures dependency among subsystems
  - High coupling: Changes to one subsystem will have high impact on the other subsystem
  - Low coupling: A change in one subsystem does not affect any other subsystem.

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Coupling and Coherence of Subsystems

Good Design

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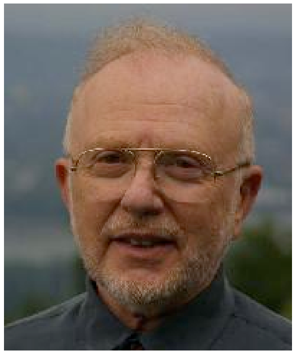
How to achieve high Coherence

- High coherence can be achieved if most of the interaction is within subsystems, rather than across subsystem boundaries
- Questions to ask:
  - Does one subsystem always call another one for a specific service?
    - Yes: Consider moving them together into the same subystem.
  - Which of the subsystems call each other for services?
    - Can this be avoided by restructuring the subsystems or changing the subsystem interface?
  - Can the subsystems even be hierarchically ordered (in layers)?

How to achieve Low Coupling

- Low coupling can be achieved if a calling class does not need to know anything about the internals of the called class (Principle of information hiding, Parnas)
- Questions to ask:
  - Does the calling class really have to know any attributes of classes in the lower layers?
  - Is it possible that the calling class calls only operations of the lower level classes?

David Parnas, *1941,
Developed the concept of
modularity in design.



Architectural Style & Software Architecture

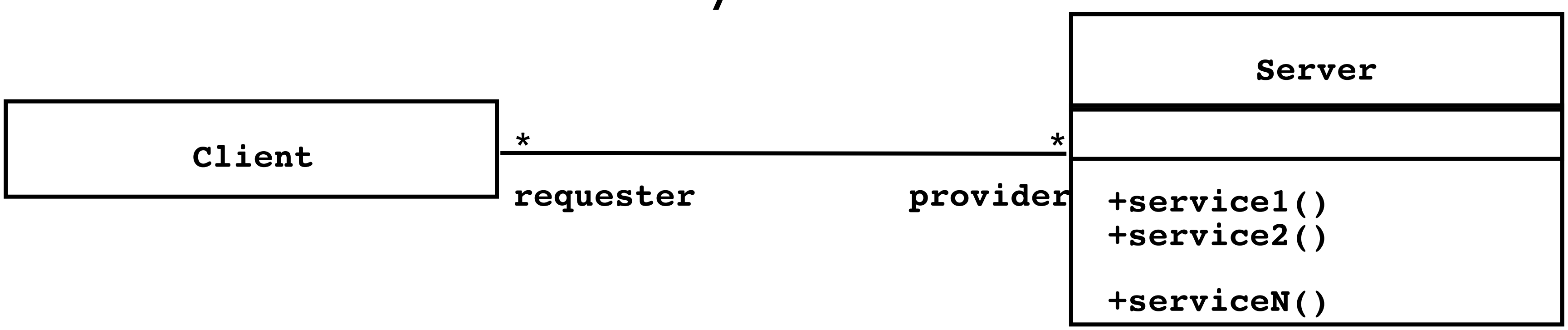
- Subsystem decomposition: Identification of subsystems, services, and their relationship to each other.
- Architectural Style: A pattern for subsystem decomposition
- Software Architecture: Instance of an architectural style

Examples of Architectural Styles

- Client/Server
- Peer-To-Peer
- Repository
- Model/View/Controller
- Three-tier, Four-tier Architecture
- Service-Oriented Architecture (SOA)
- Pipes and Filters

Client/Server Architectural Style

- One or many servers provide services to instances of subsystems, called clients
- Each client calls on the server, which performs some service and returns the result
  - The clients know the *interface* of the server
  - The server does not need to know the interface of the client
- The response in general is immediate
- End users interact only with the client.



Client/Server Architectures

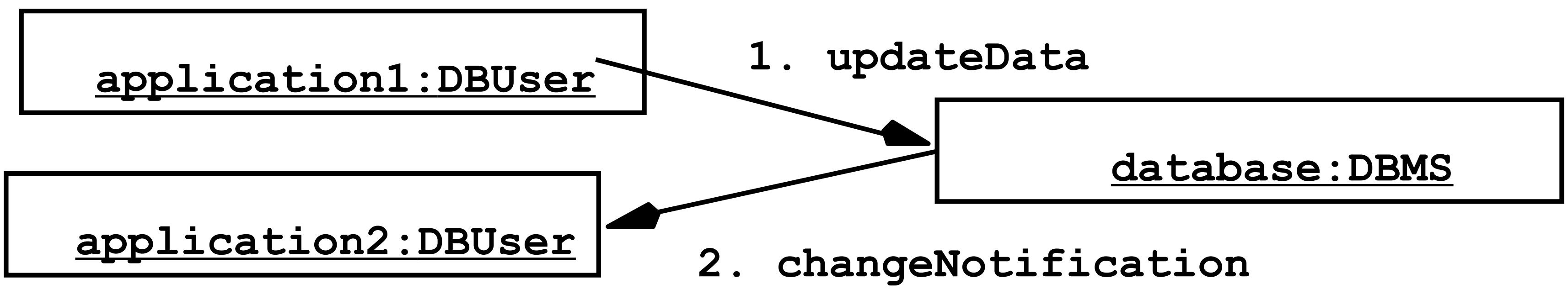
- Often used in the design of database systems
  - Front-end: User application (client)
  - Back end: Database access and manipulation (server)
- Functions performed by client:
  - Input from the user (Customized user interface)
  - Front-end processing of input data
- Functions performed by the database server:
  - Centralized data management
  - Data integrity and database consistency
  - Database security

Design Goals for Client/Server Architectures

Service Portability	Server runs on many operating systems and many networking environments
Location-Transparency	Server might itself be distributed, but provides a single "logical" service to the user
High Performance	Client optimized for interactive display-intensive tasks; Server optimized for CPU-intensive operations
Scalability	Server can handle large # of clients
Flexibility	User interface of client supports a variety of end devices (PDA, Handy, laptop, wearable computer)
Reliability	**A measure of success with which the observed behavior of a system confirms to the specification of its behavior (Chapter 11: Testing)**

Problems with Client/Server Architectures

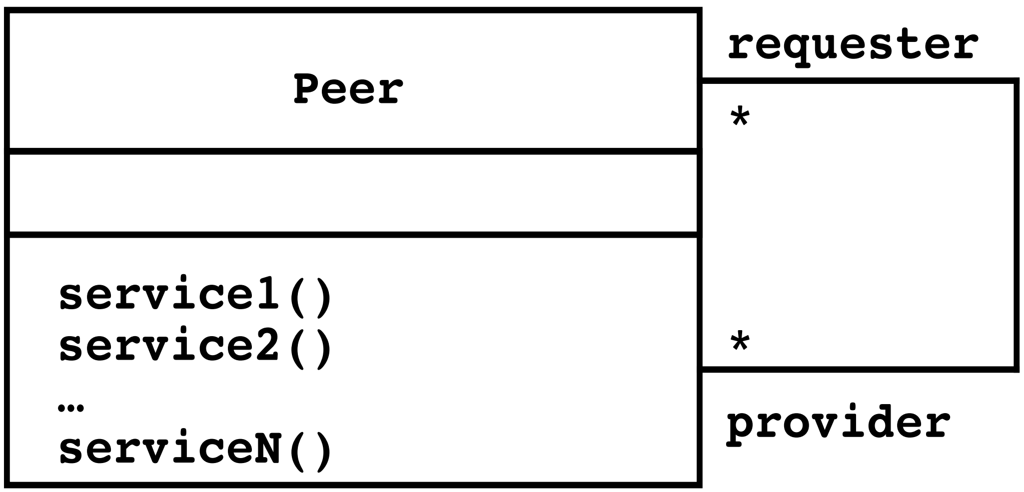
- Client/Server systems do not provide peer-to-peer communication
- Peer-to-peer communication is often needed
- Example:
  - Database must process queries from application and should be able to send notifications to the application when data have changed

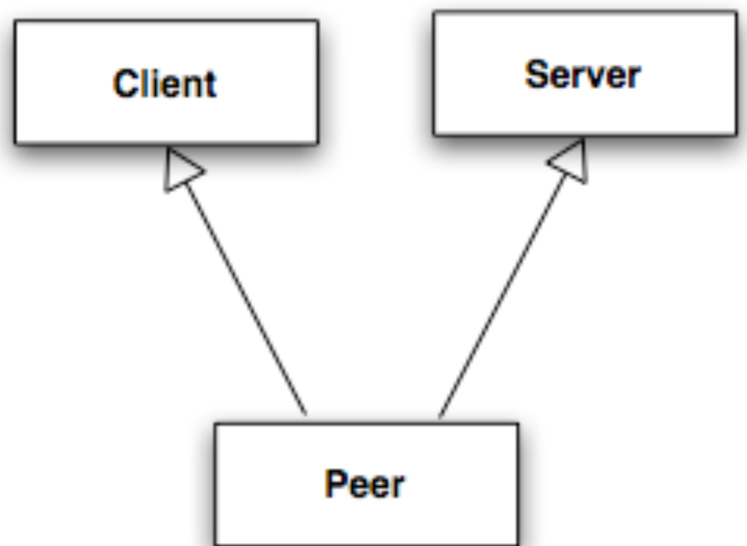


Peer-to-Peer Architectural Style

Generalization of Client/Server Architecture

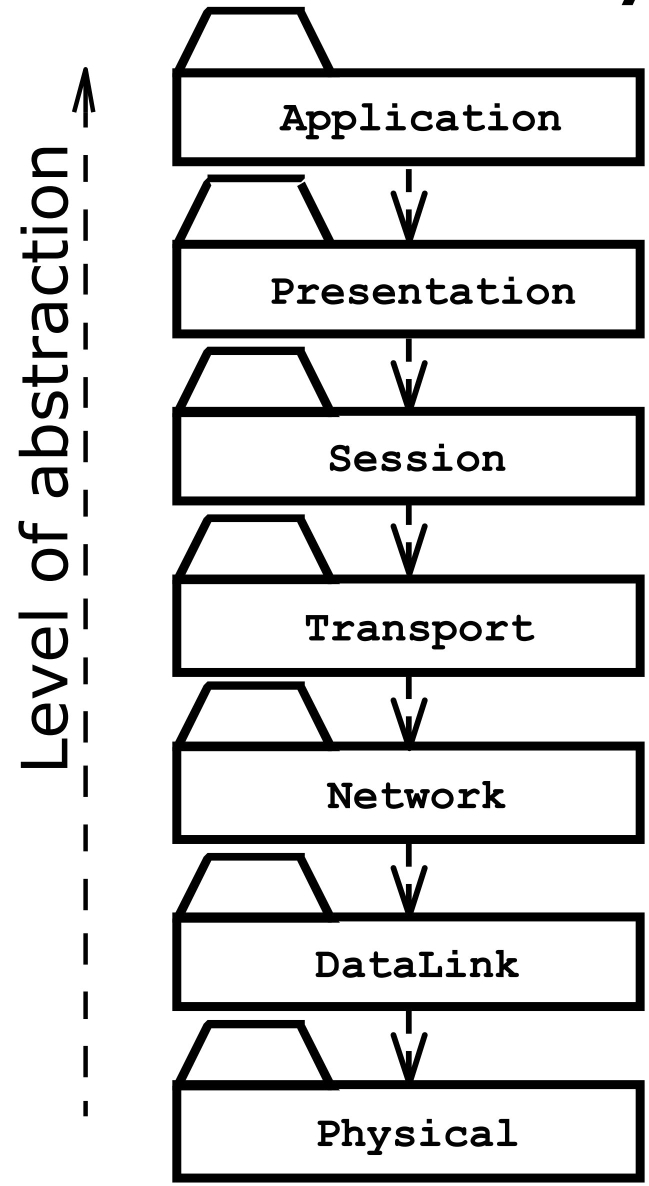
Clients can be servers and servers can be clients
=> "A peer can be a client as well as a server".





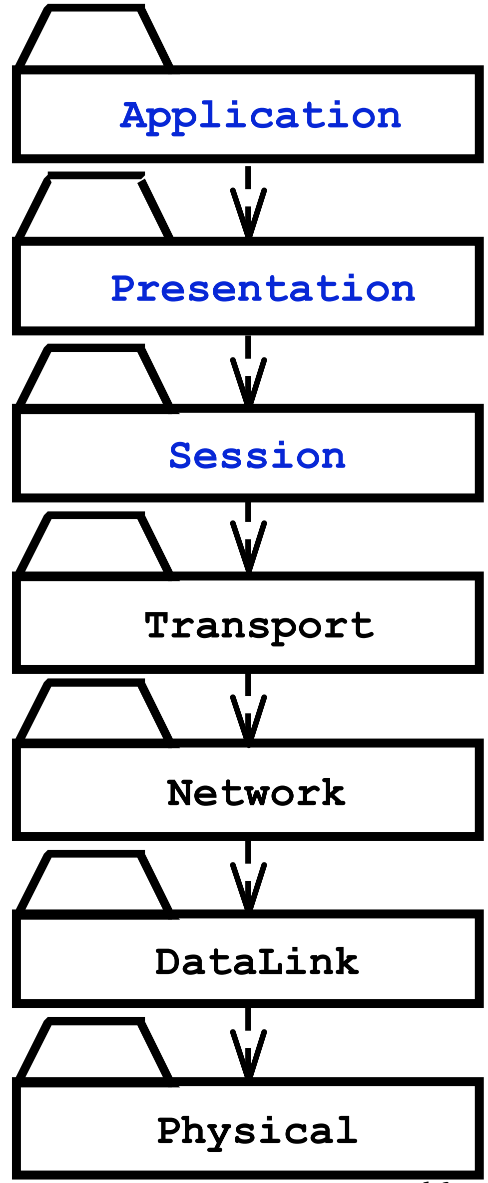
Example: Peer-to-Peer Architectural Style

- ISO's OSI Reference Model
  - ISO = International Standard Organization
  - OSI = Open System Interconnection
- Reference model which defines 7 layers and communication protocols between the layers



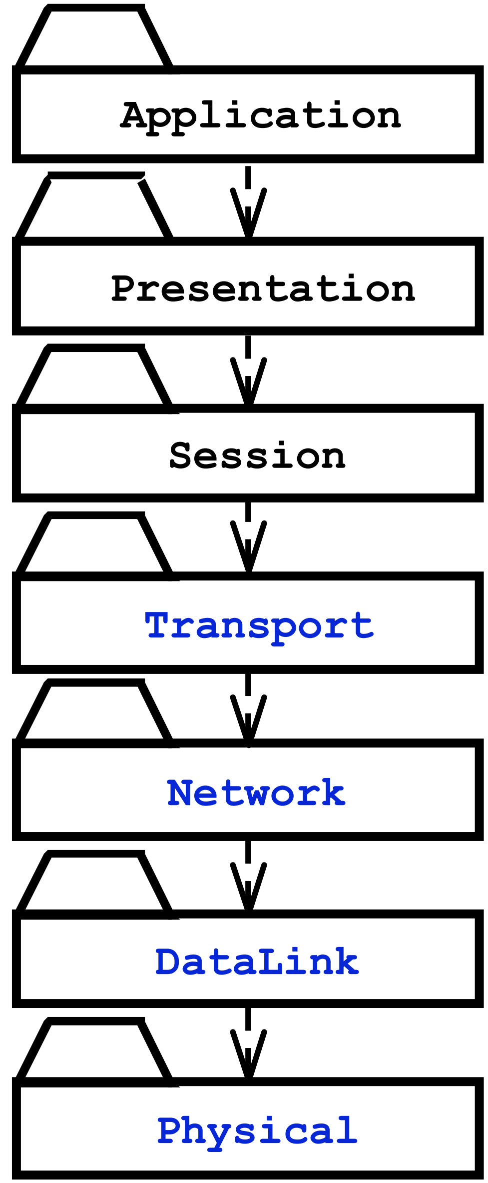
OSI Model Layers and Services

- The Application layer is the system you are building (unless you build a protocol stack)
  - ! The application layer is usually layered itself
- The Presentation layer performs data transformation services, such as byte swapping and encryption
- The Session layer is responsible for initializing a connection, including authentication

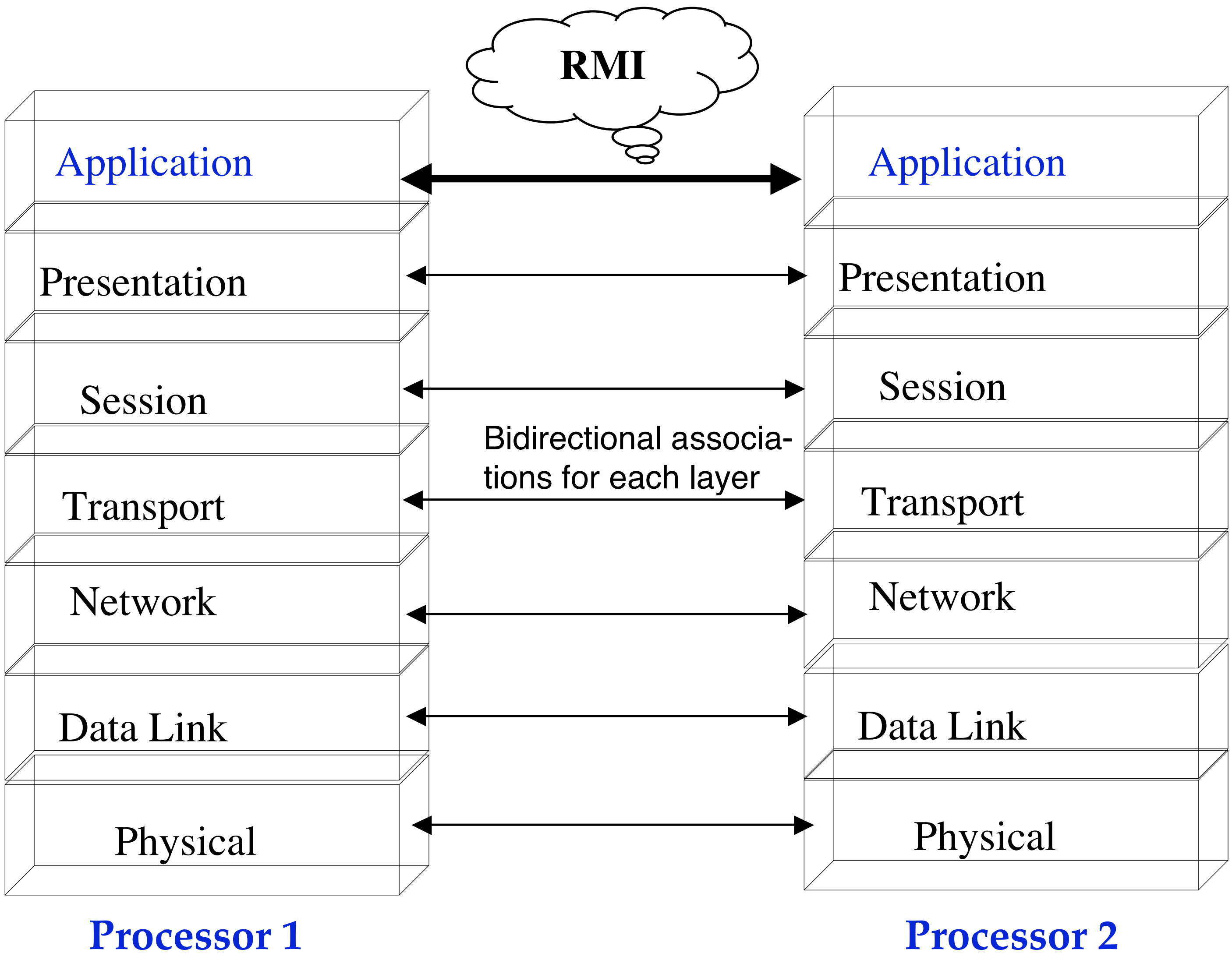


OSI Model Layers and their Services

- The Transport layer is responsible for reliably transmitting messages
  - Used by Unix programmers who transmit messages over TCP/IP sockets
- The Network layer ensures transmission and routing
  - Services: Transmit and route data within the network
- The Datalink layer models frames
  - Services: Transmit frames without error
- The Physical layer represents the hardware interface to the network
  - Services: sendBit() and receiveBit()

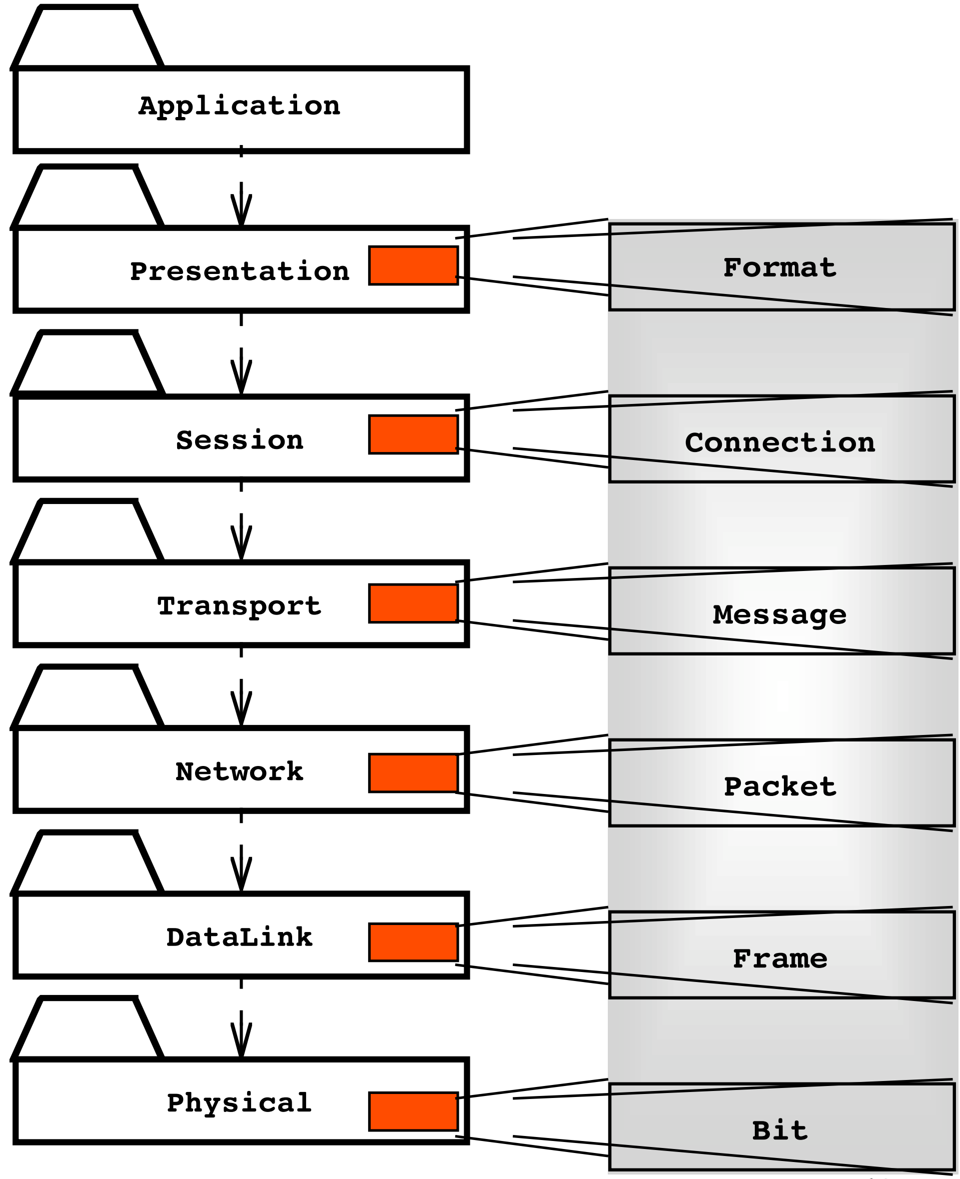


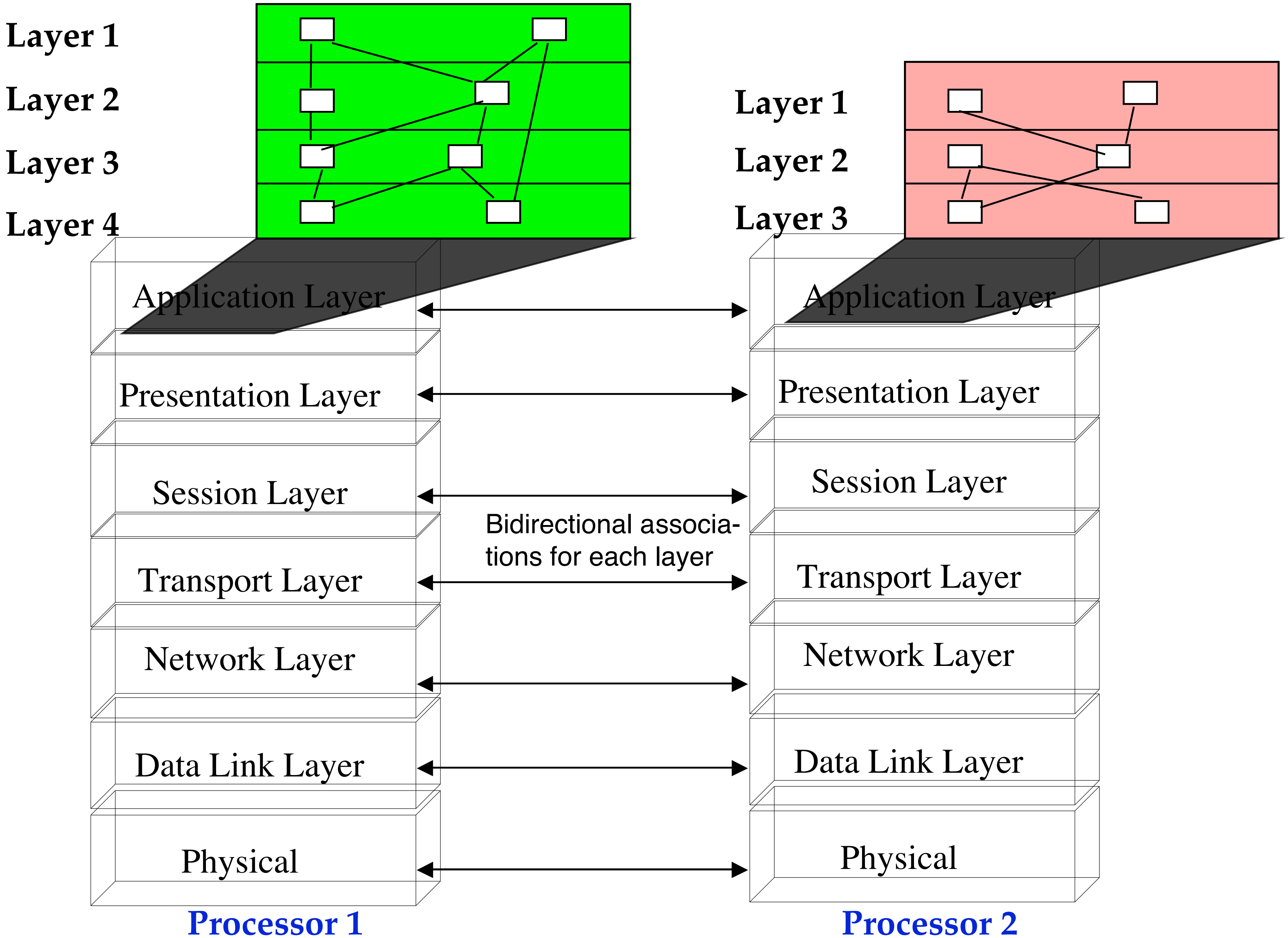
The Application Layer Provides the Abstractions of the "New System"



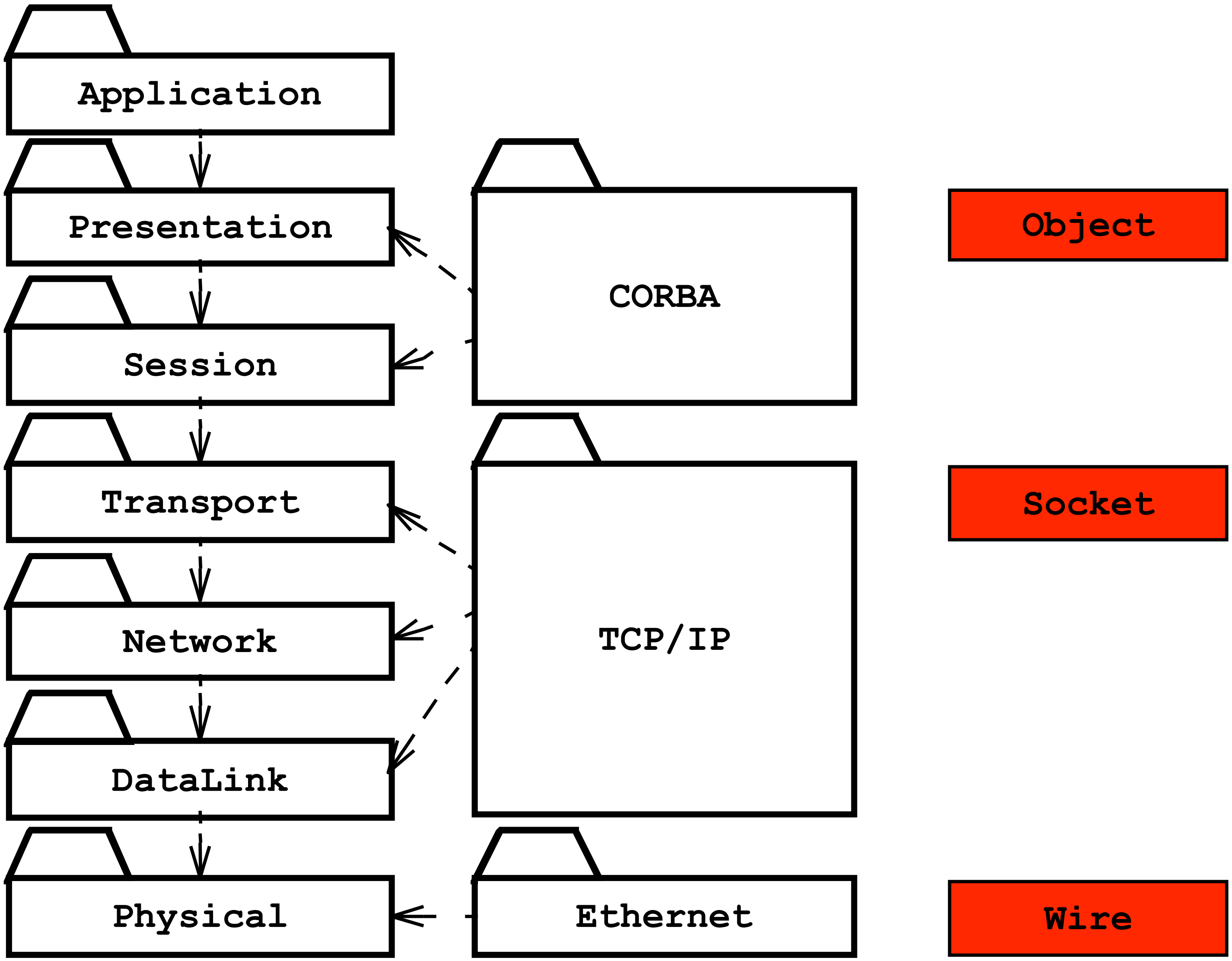
An Object-Oriented View of the OSI Model

- The OSI Model is a closed software architecture (i.e., it uses opaque layering)
- Each layer can be modeled as a UML package containing a set of classes available for the layer above



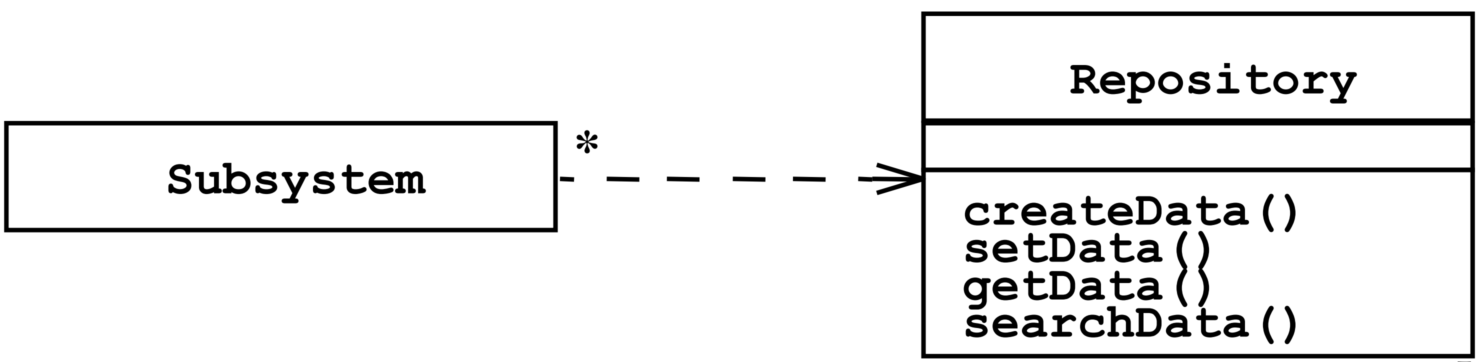

Layer 1
Layer 2
Layer 3
Layer 4
Layer 1
Layer 2
Layer 3
Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data Link Layer
Physical
Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data Link Layer
Physical
Bidirectional associa-
tions for each layer
Processor 1
Processor 2

Middleware Allows Focus On Higher Layers

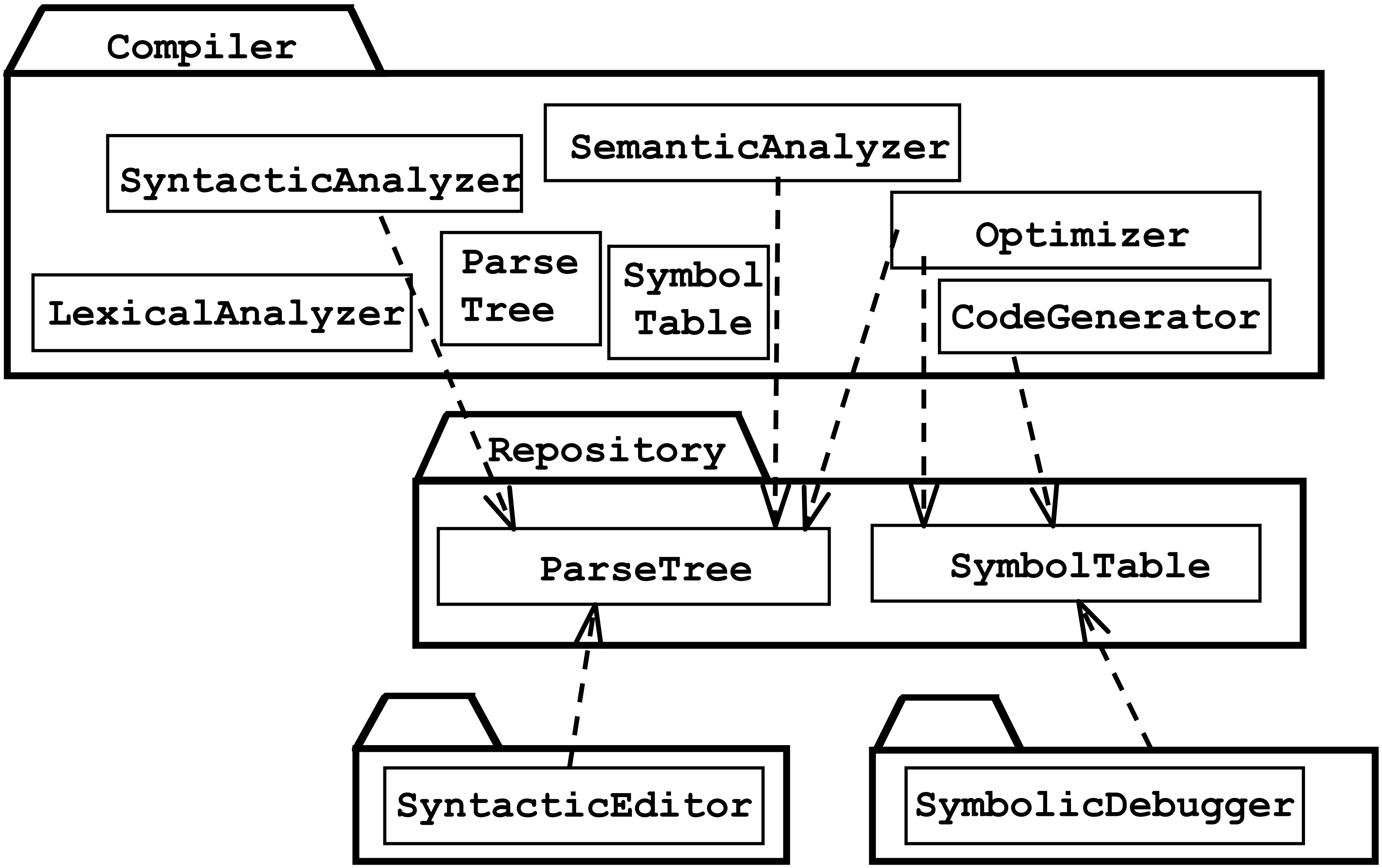


Repository Architectural Style

- Subsystems access and modify data from a single data structure called the repository
- Also called blackboard architecture
- Subsystems are loosely coupled (interact only through the repository)
- Control flow is dictated by the repository through triggers or by the subsystems through locks and synchronization primitives



Repository Architecture Example: Incremental Development Environment (IDE)



Model-View-Controller

- Problem: Assume a system with high coupling. Then changes to the boundary objects (user interface) often force changes to the entity objects (data)
  - The user interface cannot be reimplemented without changing the representation of the entity objects
  - The entity objects cannot be reorganized without changing the user interface
- Solution: The model-view-controller architectural style, which decouples data access (entity objects) and data presentation (boundary objects)
  - The Data Presentation subsystem is called the View
  - The Data Access subsystem is called the Model
    - So far this is the observer pattern!
  - The Controller is a new subsystem that mediates between View (data presentation) and Model (data access)
- Often called MVC.

Model-View-Controller Architectural Style

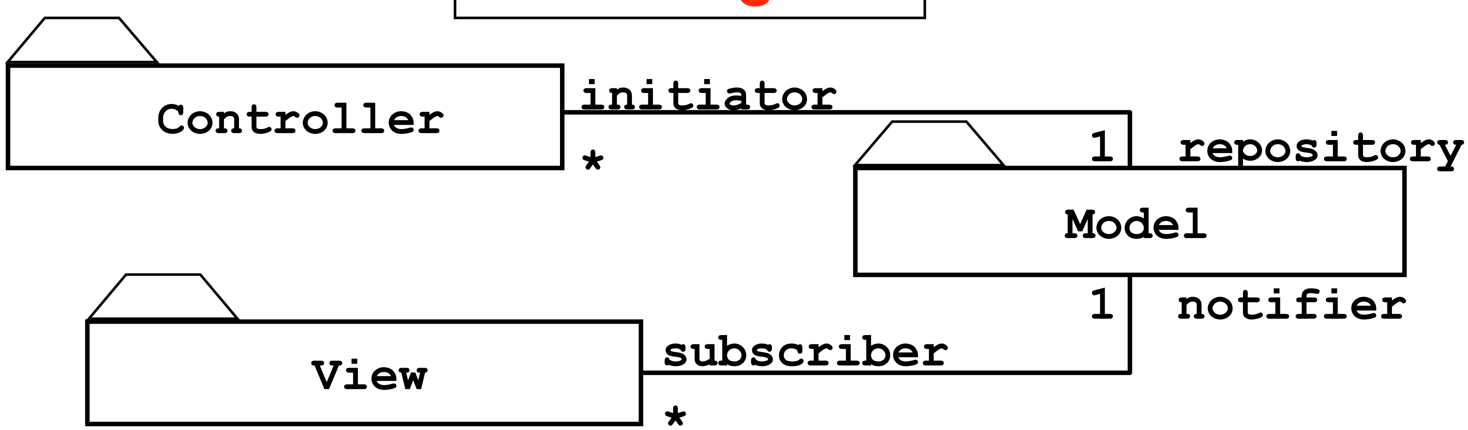
- Subsystems are classified into 3 different types

  Model subsystem: Responsible for application domain knowledge

  View subsystem: Responsible for displaying application domain objects to the user

  Controller subsystem: Responsible for sequence of interactions with the user and notifying views of changes in the model

Class Diagram

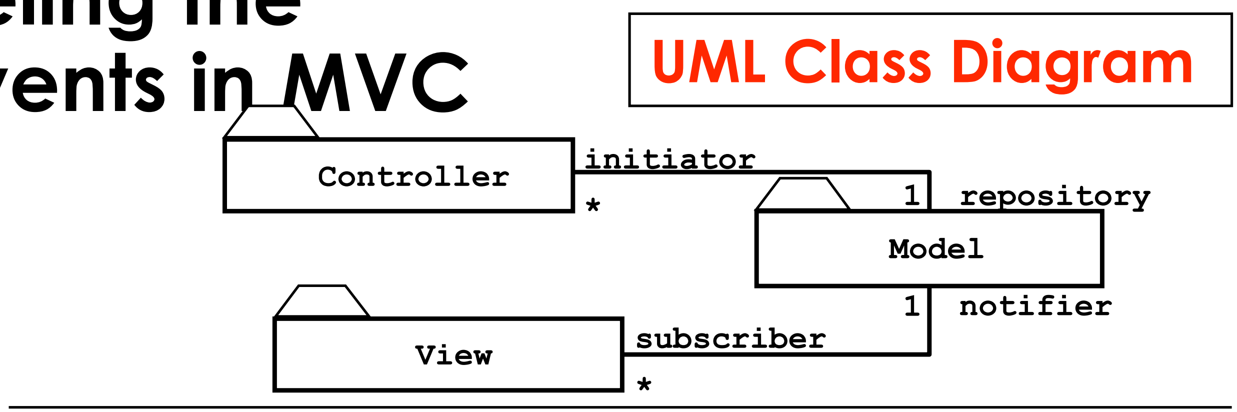


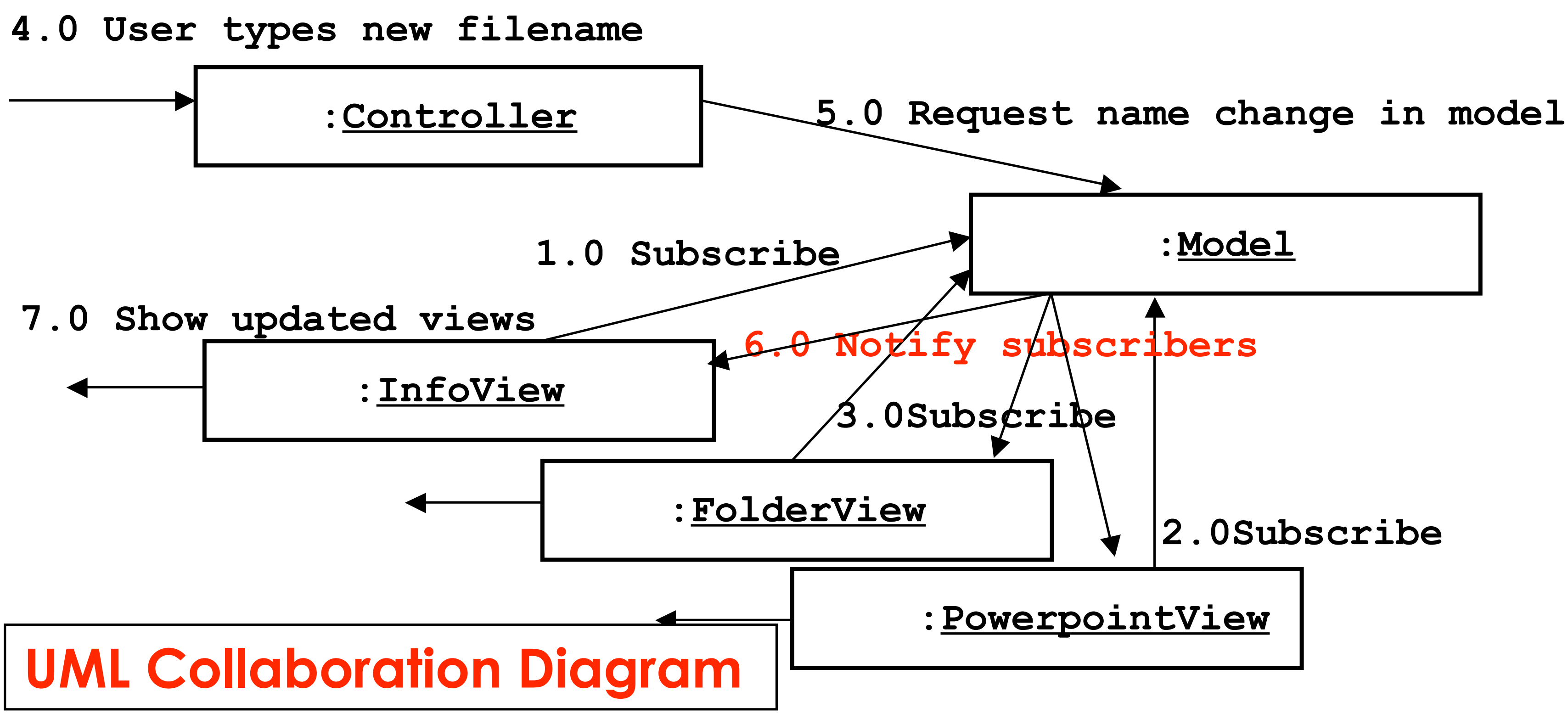
Better understanding with a Collaboration Diagram

UML Collaboration Diagram

- A Collaboration Diagram is an instance diagram that visualizes the interactions between objects as a flow of messages. Messages can be events or calls to operations
- Communication diagrams describe the static structure as well as the dynamic behavior of a system:
  - The static structure is obtained from the UML class diagram
    - Collaboration diagrams reuse the layout of classes and associations in the class diagram
  - The dynamic behavior is obtained from the dynamic model (UML sequence diagrams and UML statechart diagrams)
    - Messages between objects are labeled with a chronological number and placed near the link the message is sent over
- Reading a collaboration diagram involves starting at message 1.0, and following the messages from object to object.

Example: Modeling the Sequence of Events in MVC





3-Layer-Architectural Style
3-Tier Architecture

Definition: 3-Layer Architectura Style

- An architectural style, where an application consists of 3 hierarchically ordered subsystems
  - A user interface, middleware and a database system
  - The middleware subsystem services data requests between the user interface and the database subsystem

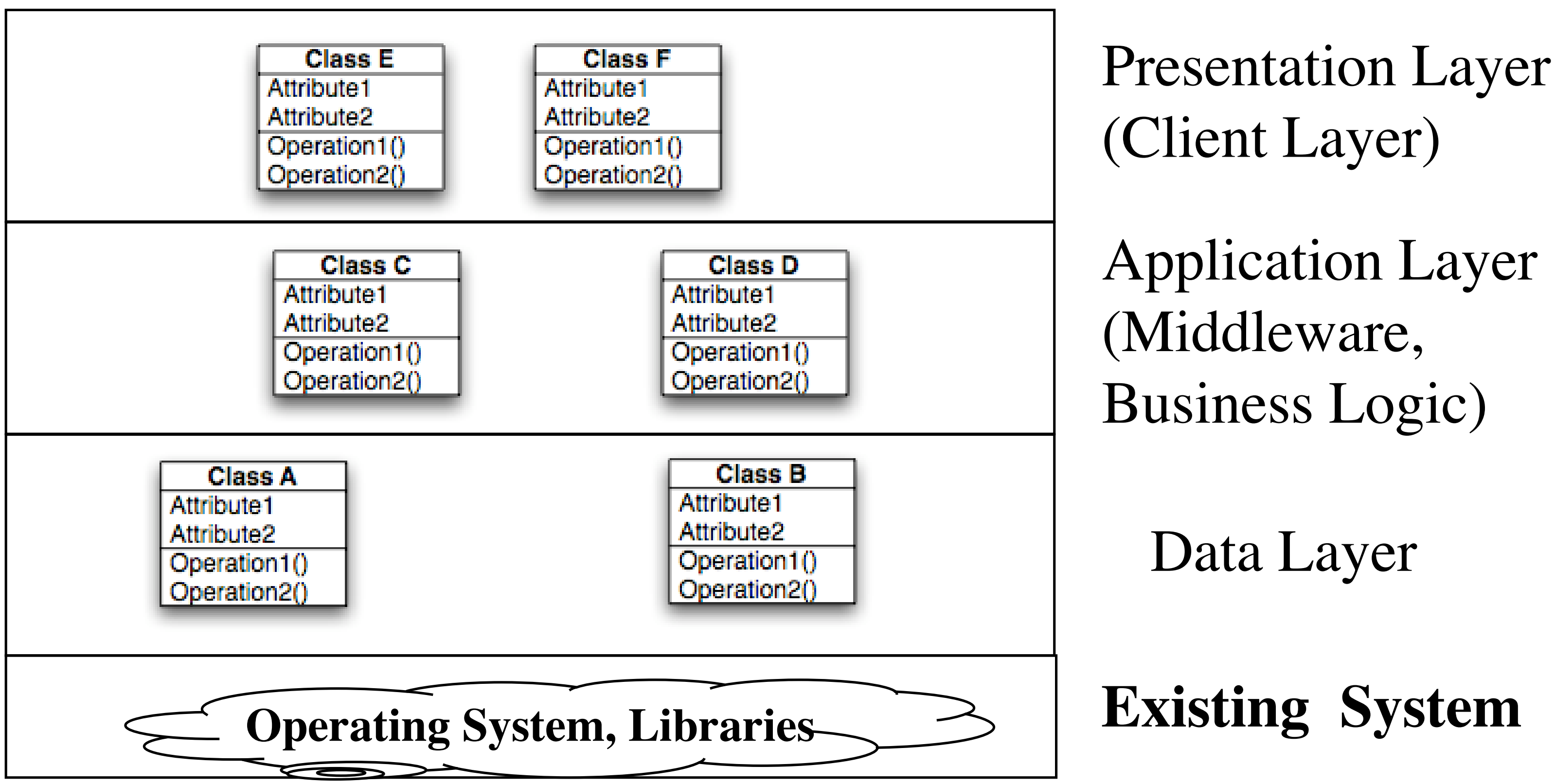
Definition: 3-Tier Architecture

- A software architecture where the 3 layers are allocated on 3 separate hardware nodes

- Note: *Layer* is a type (e.g. class, subsystem) and *Tier* is an instance (e.g. object, hardware node)
- Layer and Tier are often used interchangeably.

Virtual Machines in 3-Layer Architectural Style

A 3-Layer Architectural Style is a hierarchy of 3 virtual machines usually called presentation, application and data layer



Example of a 3-Layer Architectural Style

- Three-Layer architectural style are often used for the development of Websites:
  1. The Web Browser implements the user interface
  2. The Web Server serves requests from the web browser
  3. The Database manages and provides access to the persistent data.

Example of a 4-Layer Architectural Style

4-Layer-architectural styles (4-Tier Architectures) are usually used for the development of electronic commerce sites. The layers are

1. The Web Browser, providing the user interface
2. A Web Server, serving static HTML requests
3. An Application Server, providing session management (for example the contents of an electronic shopping cart) and processing of dynamic HTML requests
4. A back end Database, that manages and provides access to the persistent data
   - In current 4-tier architectures, this is usually a relational Database management system (RDBMS).

MVC vs. 3-Tier Architectural Style

- The MVC architectural style is nonhierarchical (triangular):
  - View subsystem sends updates to the Controller subsystem
  - Controller subsystem updates the Model subsystem
  - View subsystem is updated directly from the Model subsystem
- The 3-tier architectural style is hierarchical (linear):
  - The presentation layer never communicates directly with the data layer (opaque architecture)
  - All communication must pass through the middleware layer
- History:
  - MVC (1970-1980): Originated during the development of modular graphical applications for a single graphical workstation at Xerox Parc
  - 3-Tier (1990s): Originated with the appearance of Web applications, where the client, middleware and data layers ran on physically separate platforms.

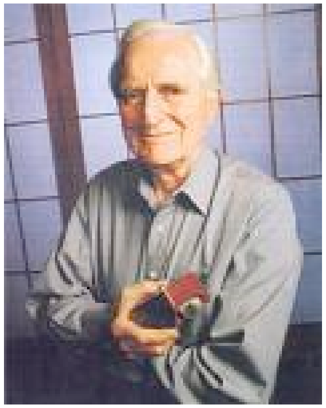
History: Xerox Parc

History at Xerox Parc

Xerox PARC (Palo Alto Research Center)

Founded in 1970 by Xerox, since 2002 a separate company PARC (wholly owned by Xerox). Best known for the invention of

- Laser printer (1973, Gary Starkweather)
- Ethernet (1973, Bob Metcalfe)
- Modern personal computer (1973, Alto, Bravo)
- Graphical user interface (GUI) based on WIMP
  - Windows, icons, menus and pointing device
    - Based on Doug Engelbart´s invention of the mouse in 1965



- Object-oriented programming (Smalltalk, 1970s, Adele Goldberg)
- Ubiquitous computing (1990, Mark Weiser).

Pipes and Filters

- A pipeline consists of a chain of processing elements (processes, threads, etc.), arranged so that the output of one element is the input to the next element
  - Usually some amount of buffering is provided between consecutive elements
  - The information that flows in these pipelines is often a stream of records, bytes or bits.

Pipes and Filters Architectural Style

- An architectural style that consists of two subsystems called pipes and filters
  - **Filter:** A subsystem that does a processing step
  - **Pipe:** A Pipe is a connection between two processing steps
- Each filter has an input pipe and an output pipe.
  - The data from the input pipe are processed by the filter and then moved to the output pipe
- Example of a Pipes-and-Filters architecture: Unix
  - Unix shell command: **ls -a** | **cat**

A pipe

The Unix shell commands **ls** and **cat** are Filter

Pipes-And-Filters

Additional Readings

- E.W. Dijkstra (1968)
  - The structure of the T.H.E Multiprogramming system, Communications of the ACM, 18(8), pp. 453-457
- D. Parnas (1972)
  - On the criteria to be used in decomposing systems into modules, CACM, 15(12), pp. 1053-1058
- L.D. Erman, F. Hayes-Roth (1980)
  - The Hearsay-II-Speech-Understanding System, ACM Computing Surveys, Vol 12. No. 2, pp 213-253
- J.D. Day and H. Zimmermann (1983)
  - The OSI Reference Model,Proc. IEEE, Vol.71, 1334-1340
- Jostein Gaarder (1991)
  - Sophie`s World: A Novel about the History of Philosophy.

Summary

- System Design
  - An activity that reduces the gap between the problem and an existing (virtual) machine
- Design Goals Definition
  - Describes the important system qualities
  - Defines the values against which options are evaluated
- Subsystem Decomposition
  - Decomposes the overall system into manageable parts by using the principles of cohesion and coherence
- Architectural Style
  - A pattern of a typical subsystem decomposition
- Software architecture
  - An instance of an architectural style
  - Client Server, Peer-to-Peer, Model-View-Controller.