Object-Oriented Software Engineering
Using UML, Patterns, and Java

System Design I: System Decomposition

Why is Design so Difficult?

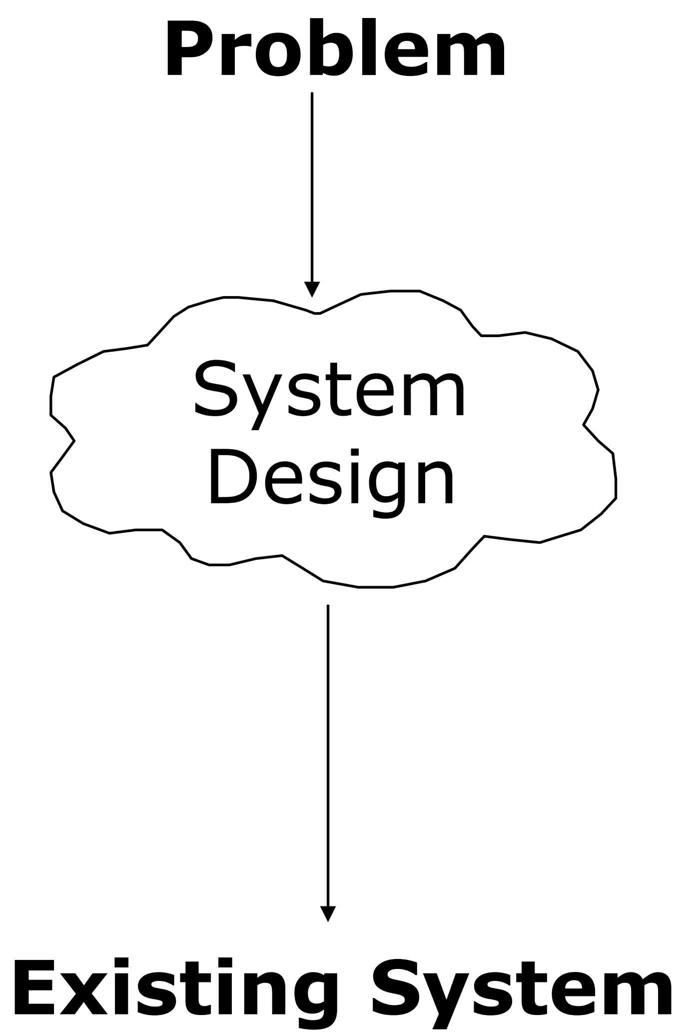
- Analysis: Focuses on the application domain
- Design: Focuses on the solution domain
  - The solution domain is changing very rapidly
    - Halftime knowledge in software engineering: About 3-5 years
    - Cost of hardware rapidly sinking
  - ➢ Design knowledge is a moving target

- 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
- Architectural Style
- 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

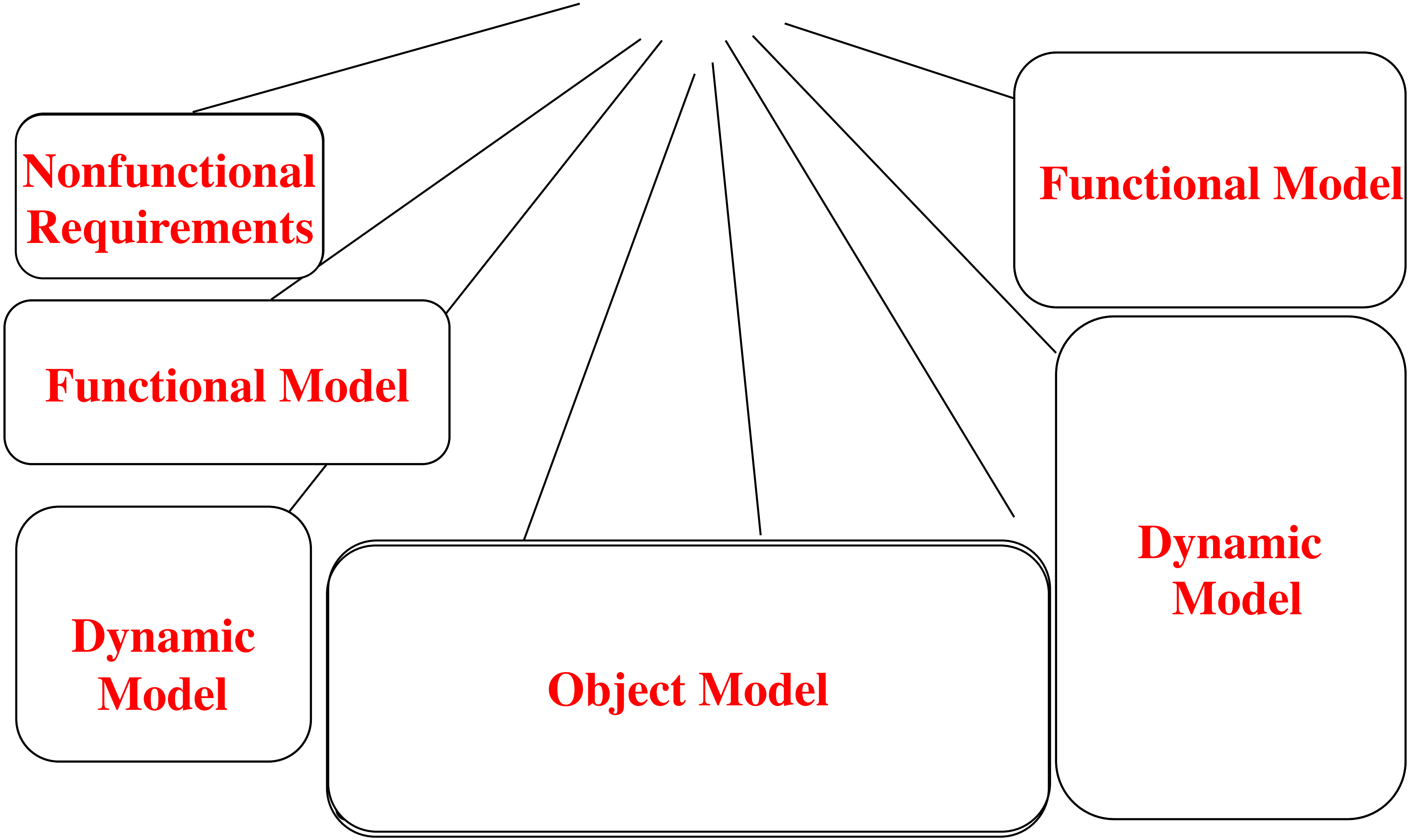
System Design I (This Lecture)

0. Overview of System Design
1. Design Goals
2. Subsystem Decomposition, Architectural Styles

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 Sources: Requirements and System Model



From Analysis to System Design

Nonfunctional Requirements

1. Design Goals
- Definition
- Trade-offs

Functional Model

2. System Decomposition
- Layers vs Partitions
- Coherence/Coupling
- Architectural Style

Dynamic Model

3. Concurrency
- Identification of Threads

Object Model

4. Hardware/ Software Mapping
- Special Purpose Systems
- Buy vs Build
- Allocation of Resources
- Connectivity

5. Data Management
- Persistent Objects
- Filesystem vs Database

Functional Model

8. Boundary Conditions
- Initialization
- Termination
- Failure

Dynamic Model

7. Software Control
- Monolithic
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- Access Control List vs Capabilities
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System Design Phases

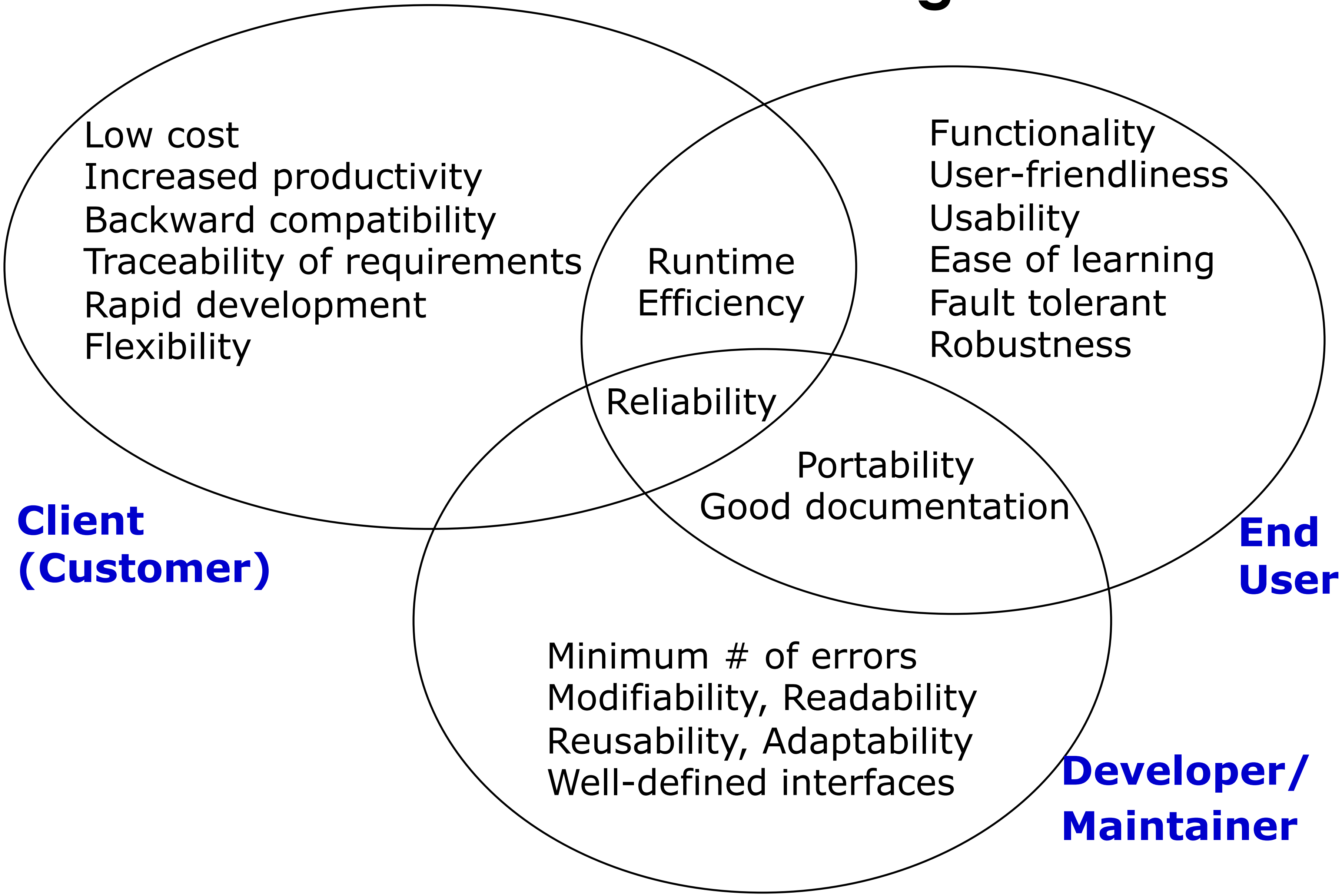
1) Design Goals
2) System Decomposition
3) Concurrency
4) Hardware/Software Mapping
5) Data Management
6) Global Resource Handling
7) Software Control
8) Boundary Conditions

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

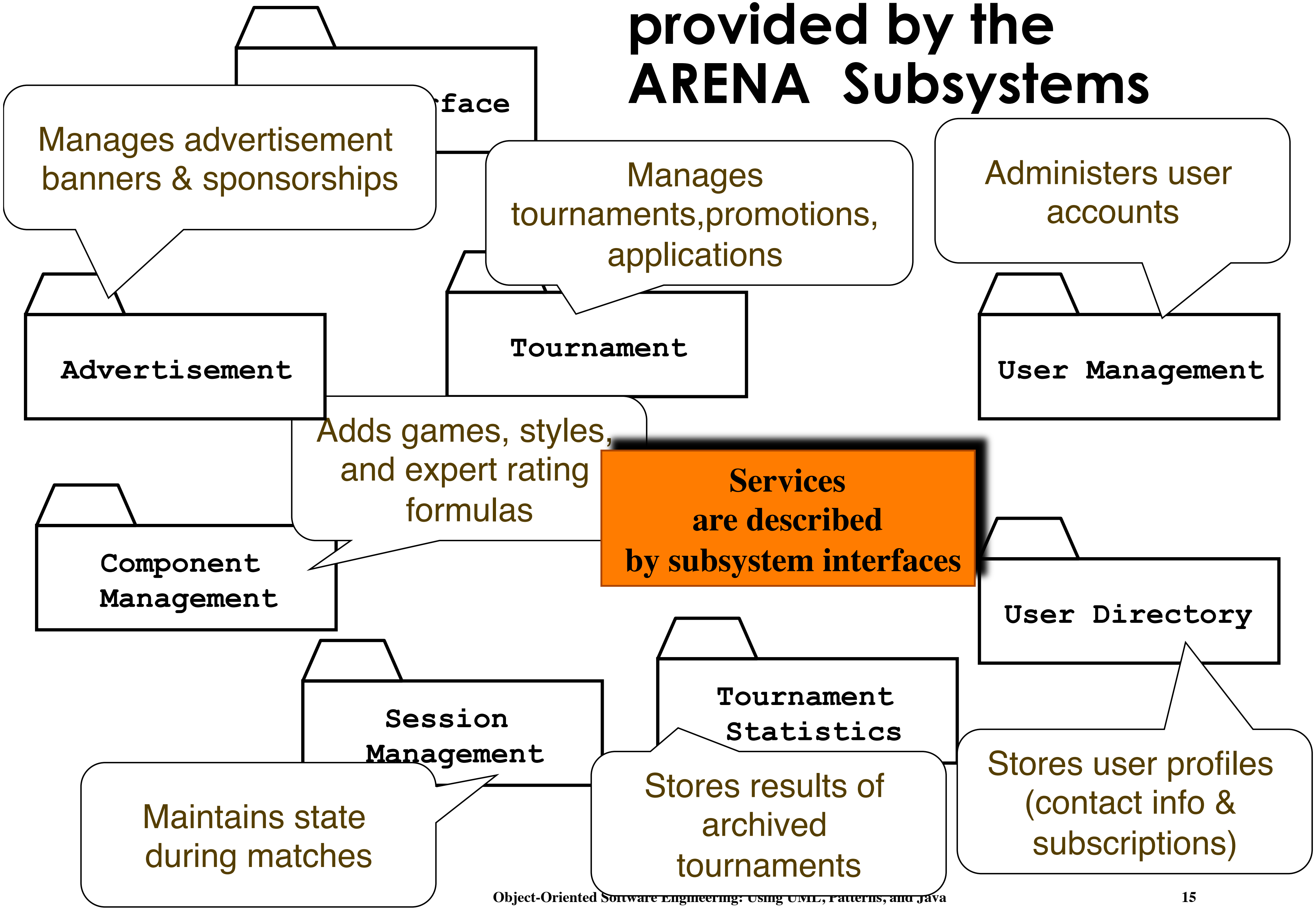
System Design Phases

1) Design Goals
2) System Decomposition
3) Concurrency
4) Hardware/Software Mapping
5) Data Management
6) Global Resource Handling
7) Software Control
8) Boundary Conditions

Subsystems and Services

- Subsystem
  - Collection of classes, associations, operations, events that are closely interrelated with each other
  - The classes in the object model are the "seeds" for subsystems
- Service
  - A group of externally visible operations provided by a subsystem (also called subsystem interface)
  - The use cases in the functional model provide the "seeds" for services

Example: Services provided by the ARENA Subsystems



Subsystem Interface and 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.*

Subsystems relationships

Coherence and Coupling

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.

Coupling and Coherence of Subsystems

Good System Design

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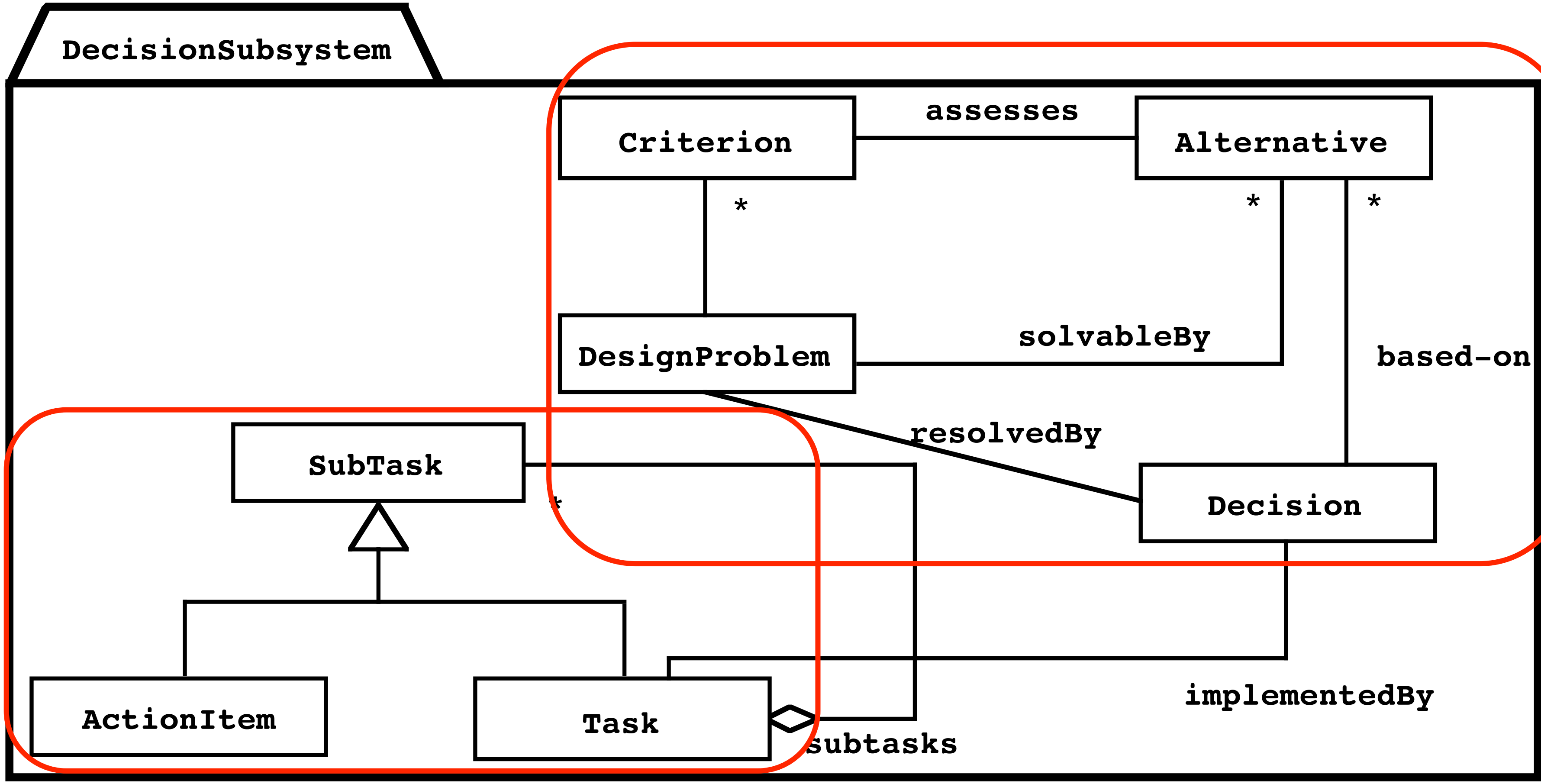
How to achieve high Coherence

- 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)?

An example: the Decision tracking system

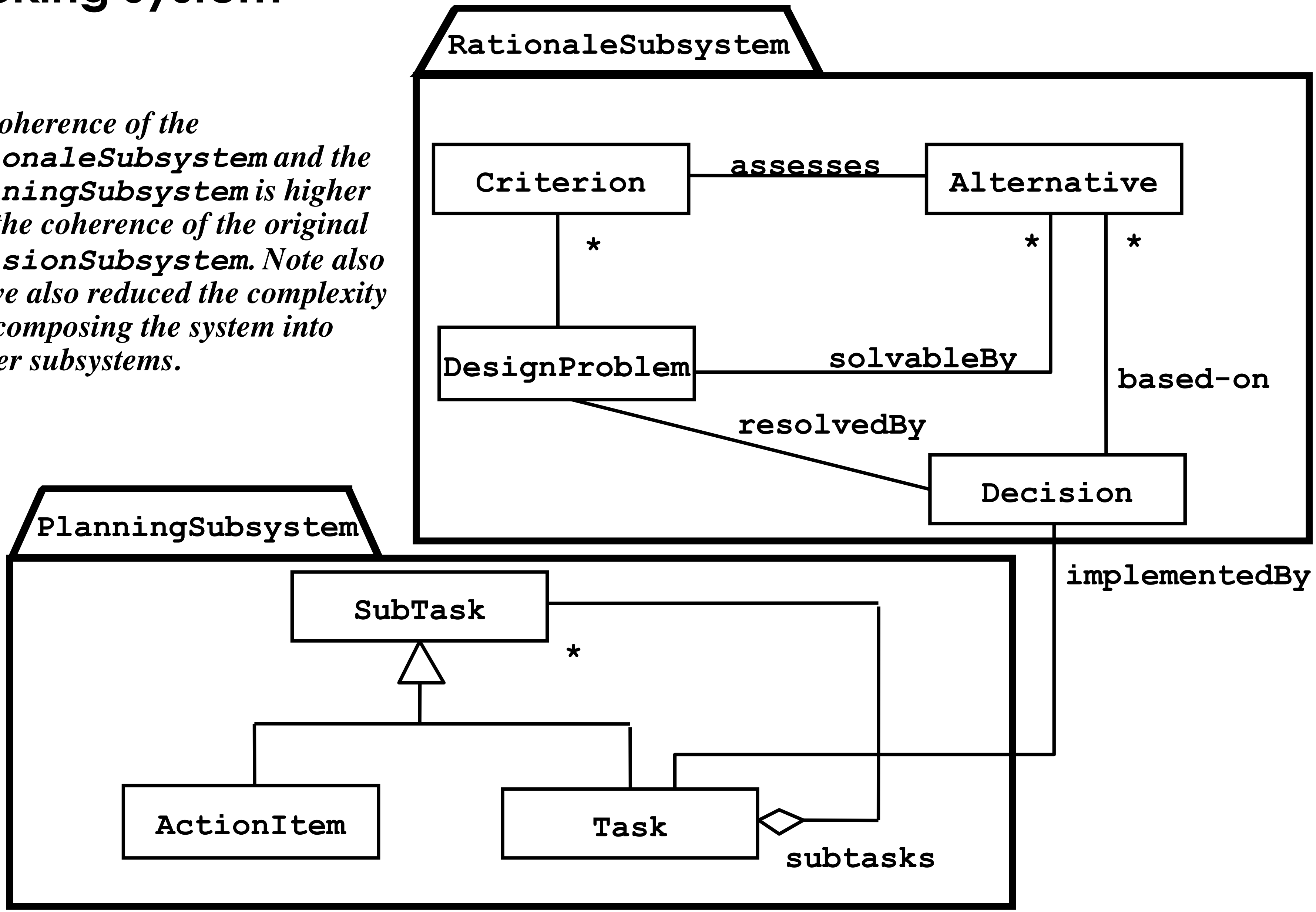
The decision tracking system purpose is to record design problems, discussions, alternative evaluations, decisions, and their implementations in terms of tasks



*The **DecisionSubsystem** has a low coherence: The classes **Criterion**, **Alternative**, and **DesignProblem** have no relationships with **Subtask**, **ActionItem**, and **Task**.*

Alternative subsystem decomposition for the decision tracking system

The coherence of the **`RationaleSubsystem`** ***and the*** **`PlanningSubsystem`** ***is higher than the coherence of the original*** **`DecisionSubsystem`**. ***Note also that we also reduced the complexity by decomposing the system into smaller subsystems.***

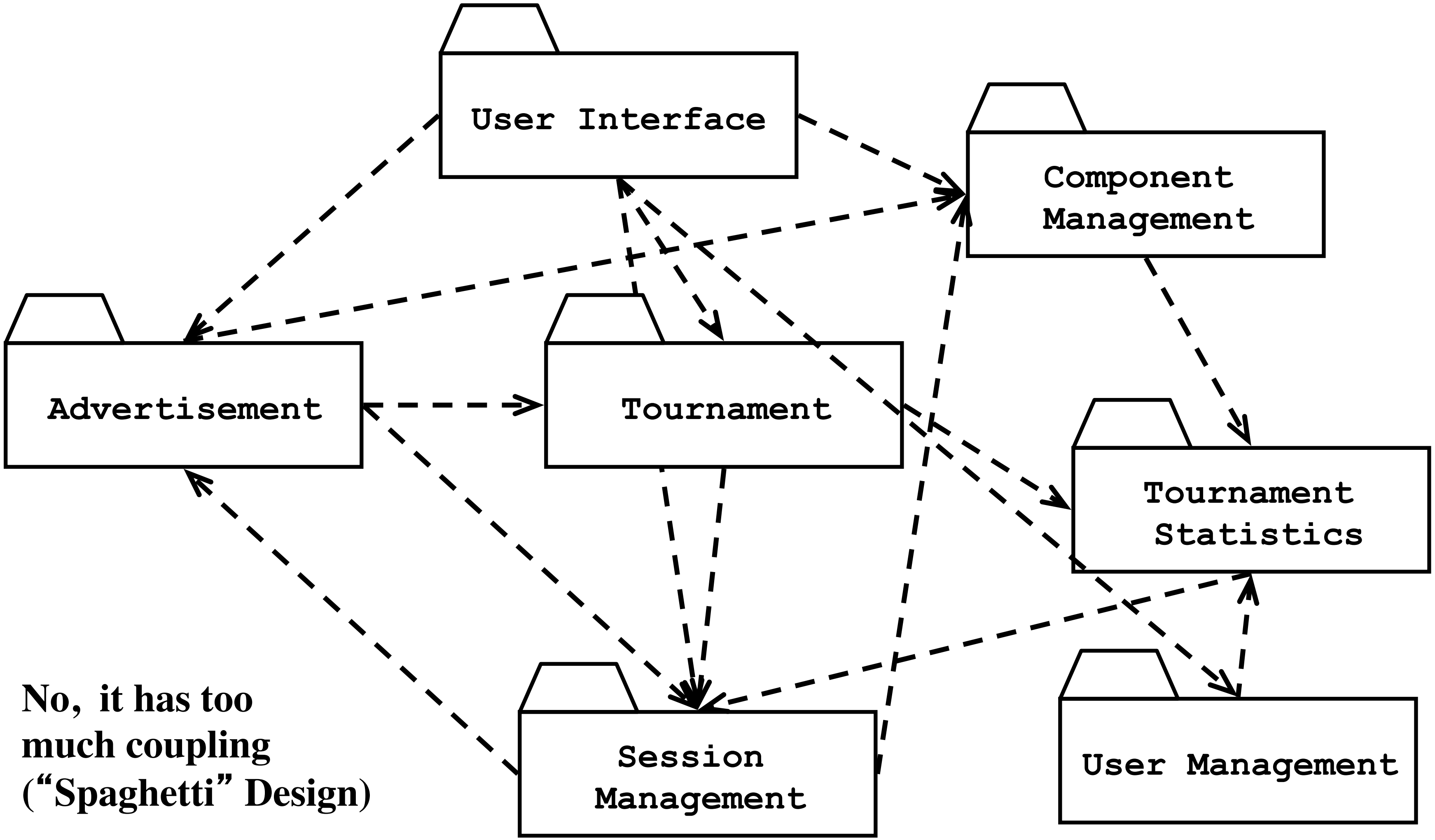


How to achieve Low Coupling

- 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)

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

Is this a Good Design?



No, it has too much coupling ("Spaghetti" Design)

Dijkstra's answer to "Spaghetti Design"

- Dijkstra revolutionary idea in 1968
  - Any system should be designed and built as a hierarchy of layers: Each layer uses only the services offered by the lower layers

Edser W. Dijkstra, 1930-2002
Formal verification: Proofs for programs
Dijkstra Algorithm, Banker's Algorithm,
Gotos considered harmful, T.H.E.,
1972 Turing Award

Architectural Style vs Architecture

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

Examples of Architectural Styles

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

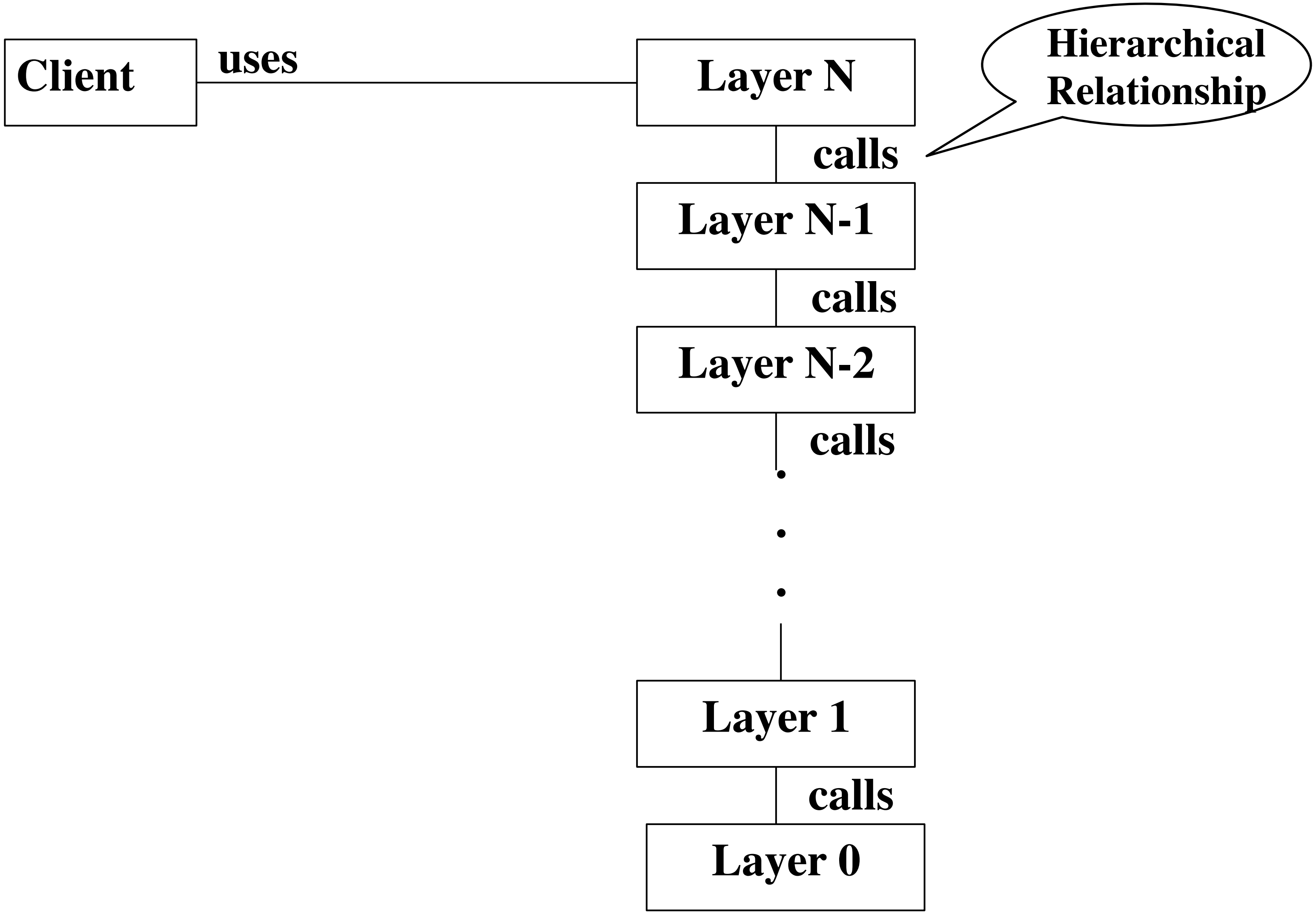
Partitions and Layers

Partitioning and layering are techniques to achieve low coupling.

A large system is usually decomposed into subsystems using both, layers and partitions.

- **Partitions** vertically divide a system into several independent (or weakly-coupled) subsystems that provide services on the same level of abstraction.
- A **layer** is a subsystem that provides services to a higher level of abstraction
  - A layer can only depend on lower layers
  - A layer has no knowledge of higher layers

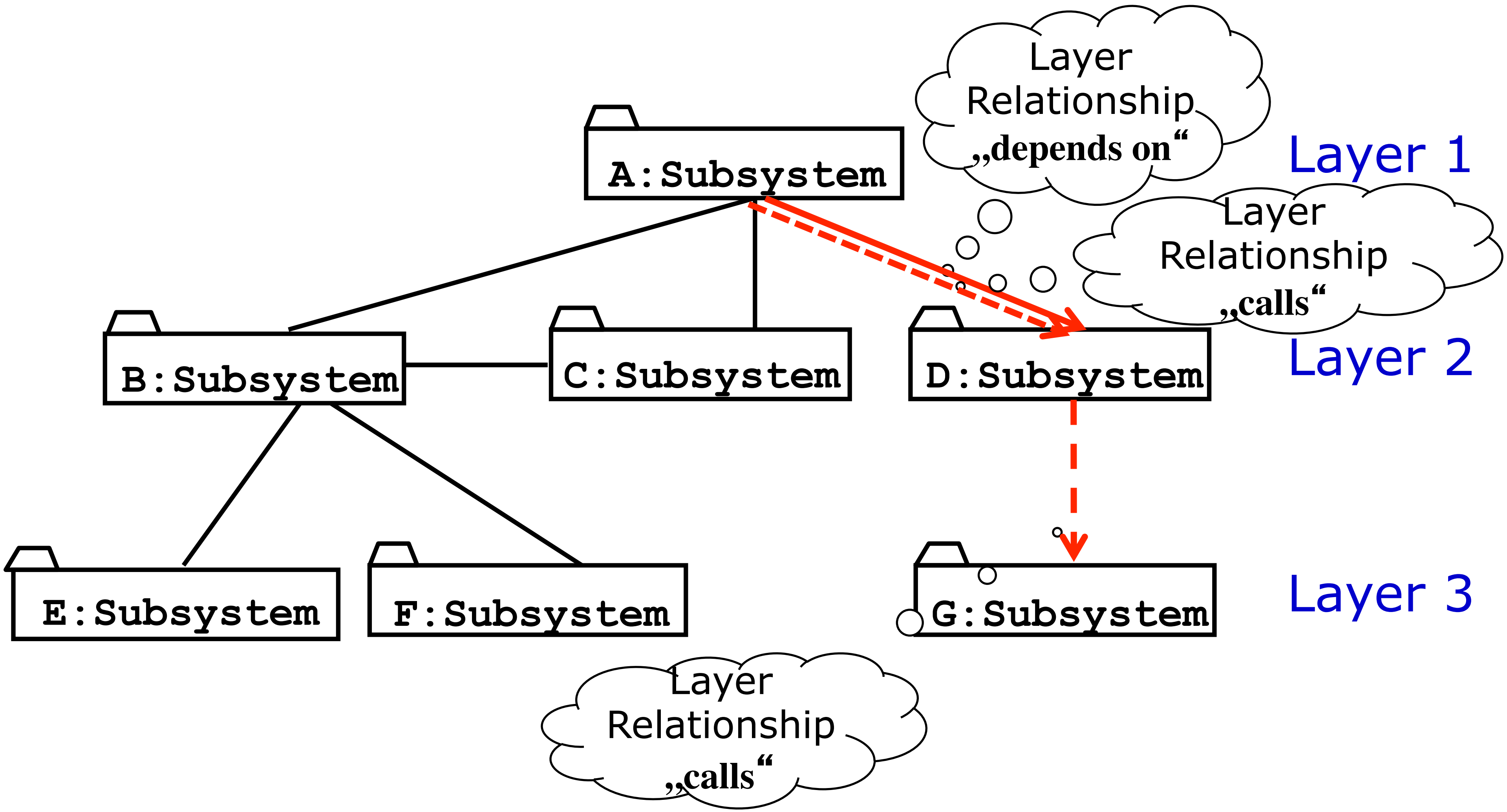
The Layered Architectural Style



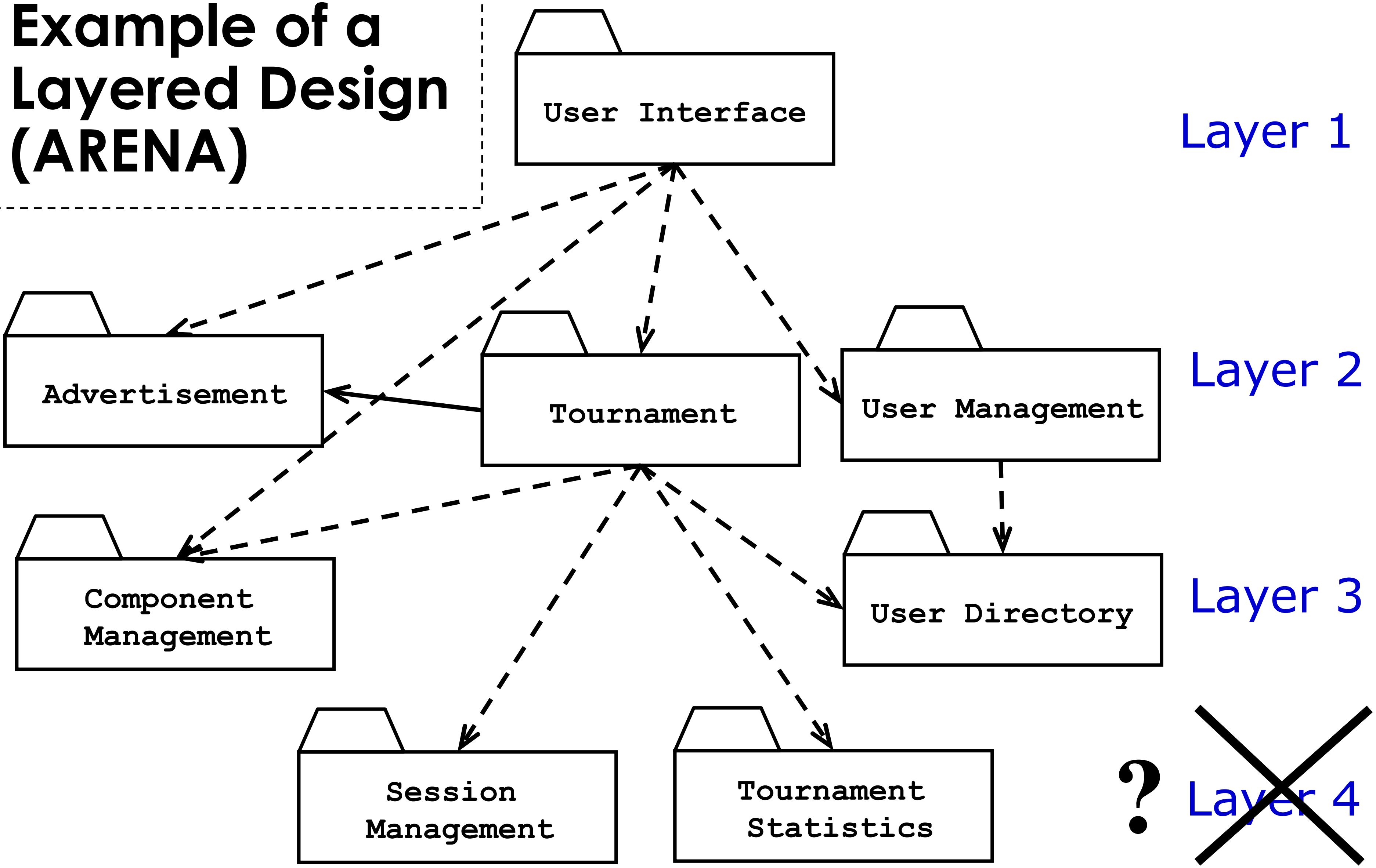
Hierarchical Relationships between Subsystems

- There are two major types of hierarchical 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!
- UML convention:
  - Runtime relationships are associations with dashed lines
  - Compile time relationships are associations with solid lines.

Example of a System with more than one Hierarchical Relationship



Example of a Layered Design (ARENA)

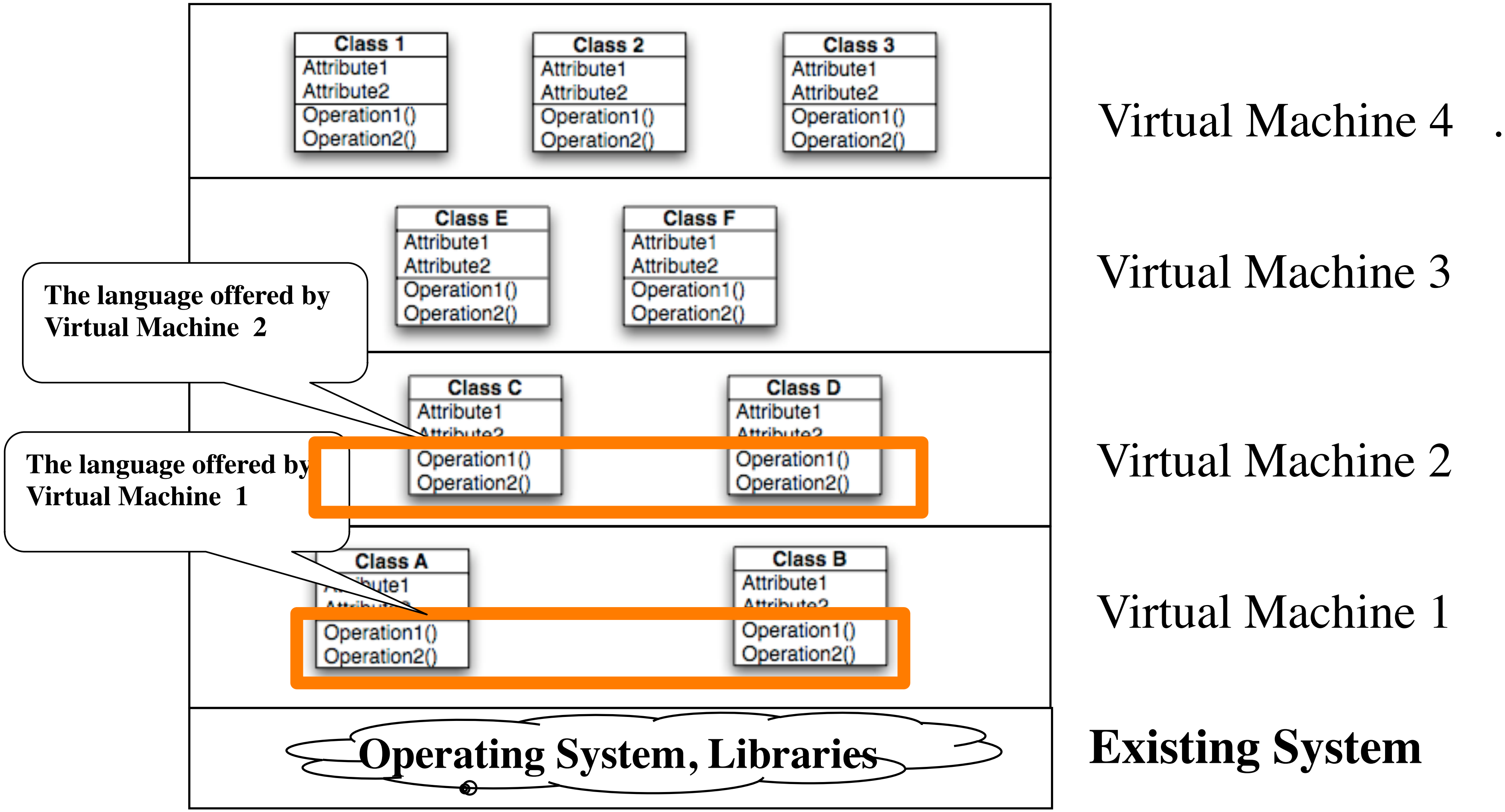


Virtual Machine

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

Building Systems as a Set of Virtual Machines

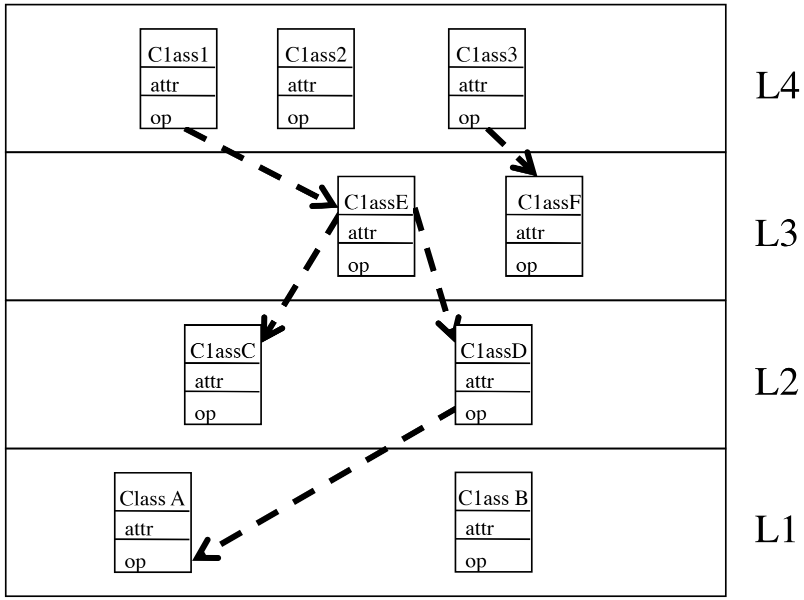
A system is a hierarchy of virtual machines, each using language primitives offered by the lower machines.



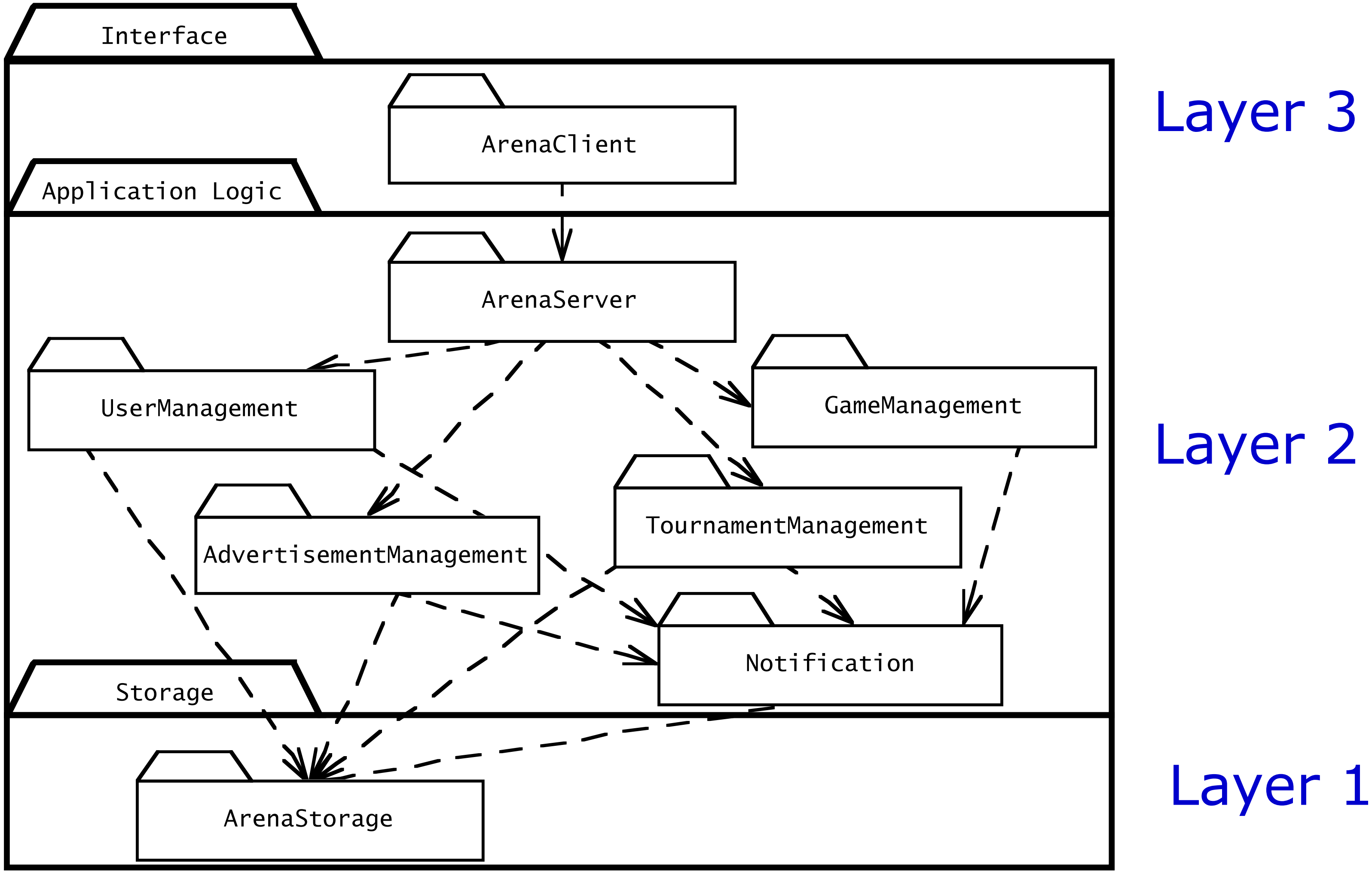
Closed Architecture (Opaque Layering)

- Each layer can only call operations from the layer below (called "direct addressing" by Buschmann et al)

Design goals:
Maintainability, flexibility.



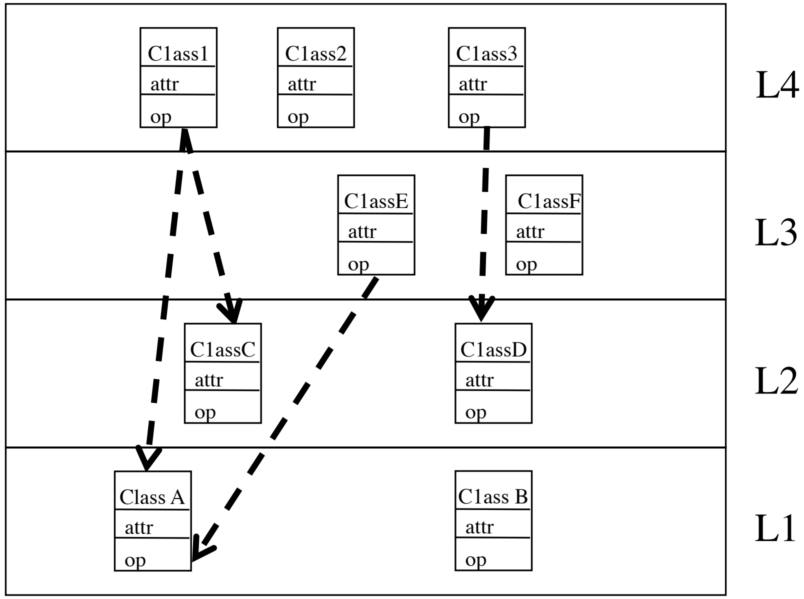
Opaque Layering in ARENA



Open Architecture (Transparent Layering)

- Each layer can call operations from any layer below ("indirect addressing")

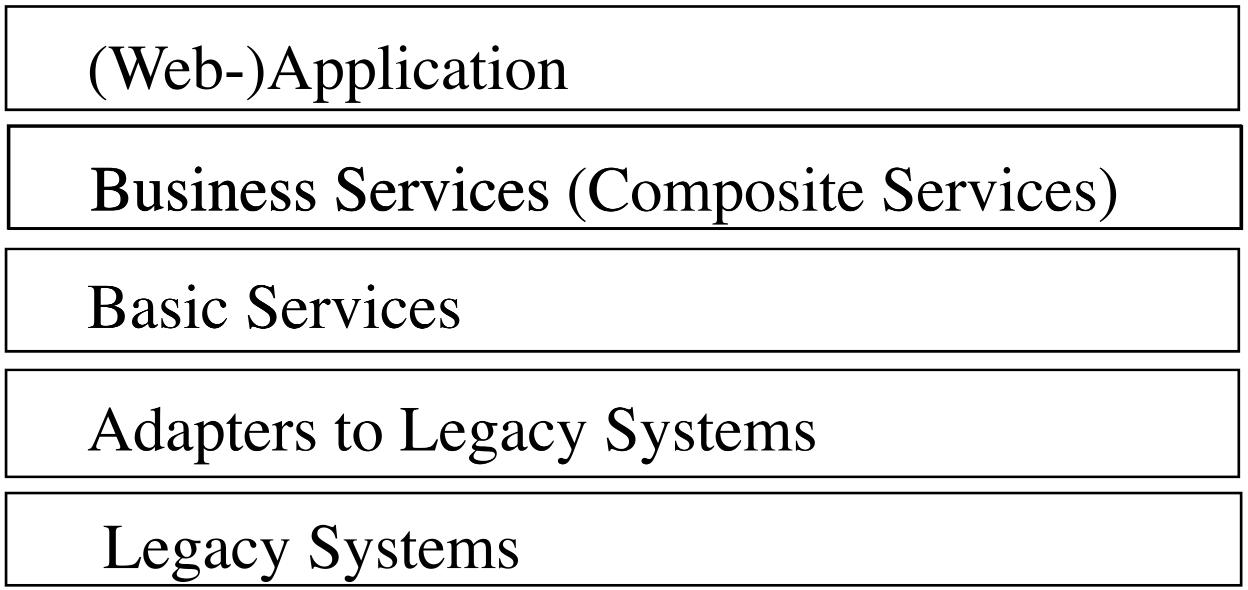
Design goal:
Runtime efficiency.



SOA is a Layered Architectural Style

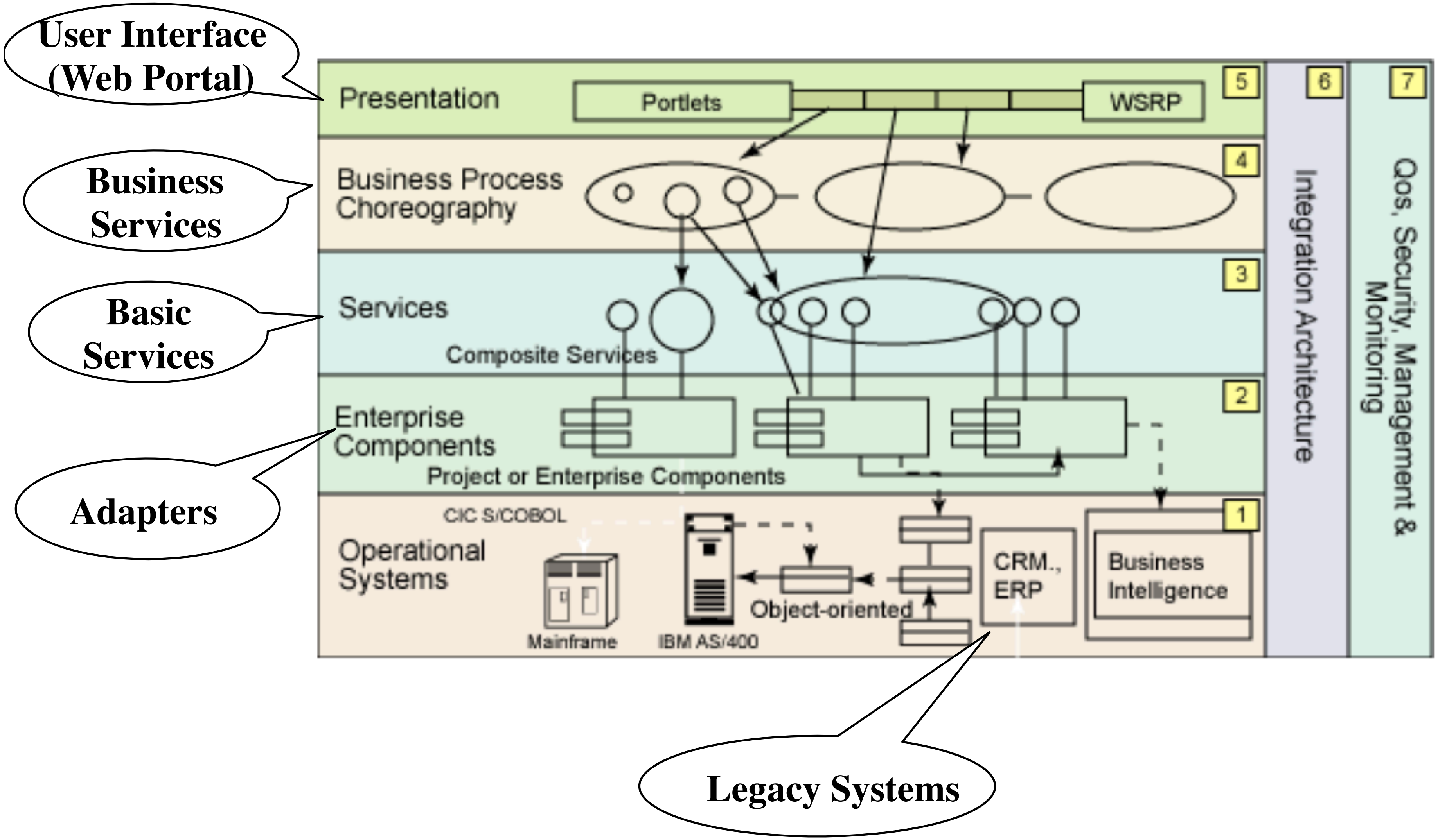
Service Oriented Architecture (SOA)

- Basic idea: A **service provider** (" business") offers business services ("business processes") to a **service consumer** (application, "customer")
  - The business services are dynamically discoverable, usually offered in web-based applications
- The business services are created by composing (choreographing) them from lower-level services (basic services)
- The basic services are usually based on legacy systems
- Adapters are used to provide the "glue" between basic services and the legacy systems.



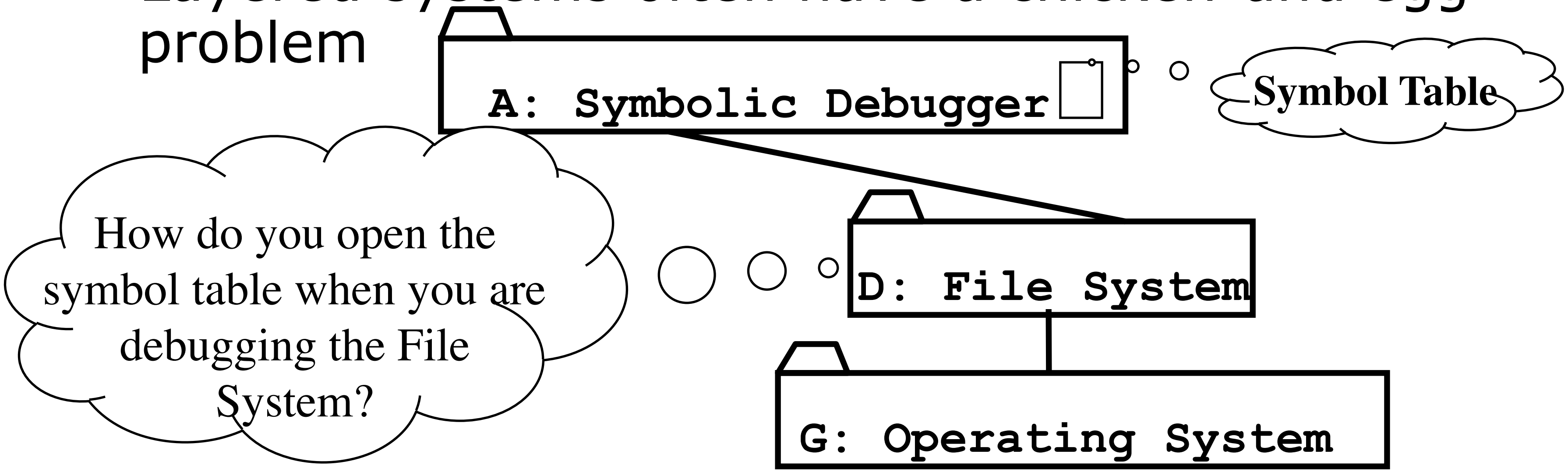
IBM's View of a Service Oriented Architecture

Source http://www.ibm.com/developerworks/webservices/library/ws-soa-design1/



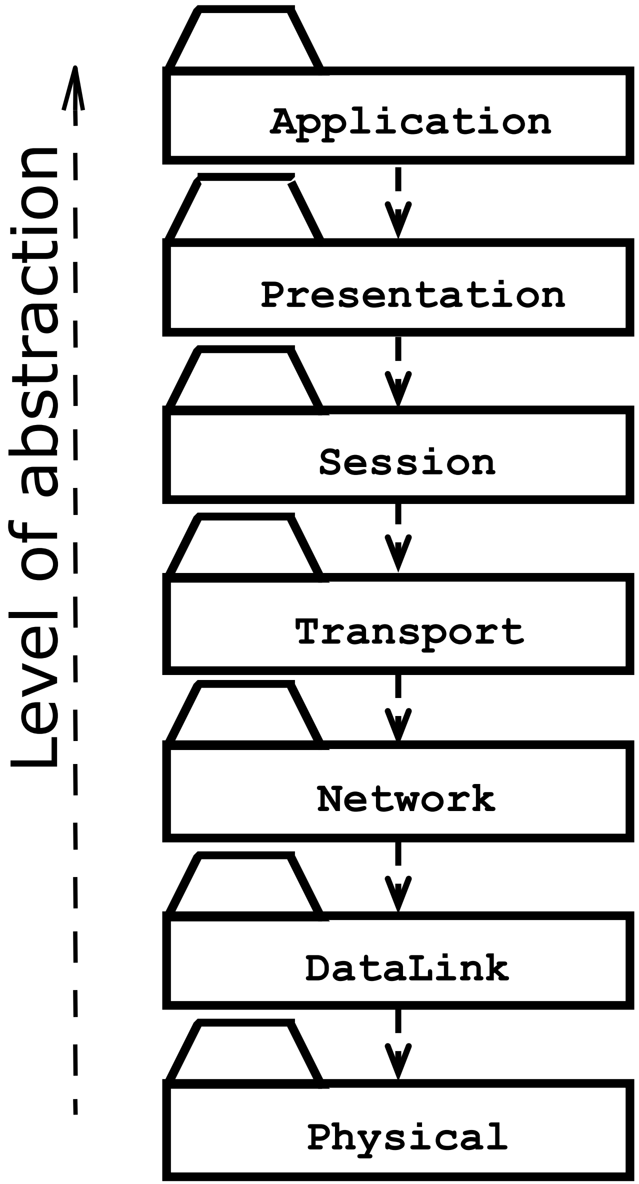
Properties of Layered Systems

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



Another Example of a Layered 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



Examples of Architectural Styles

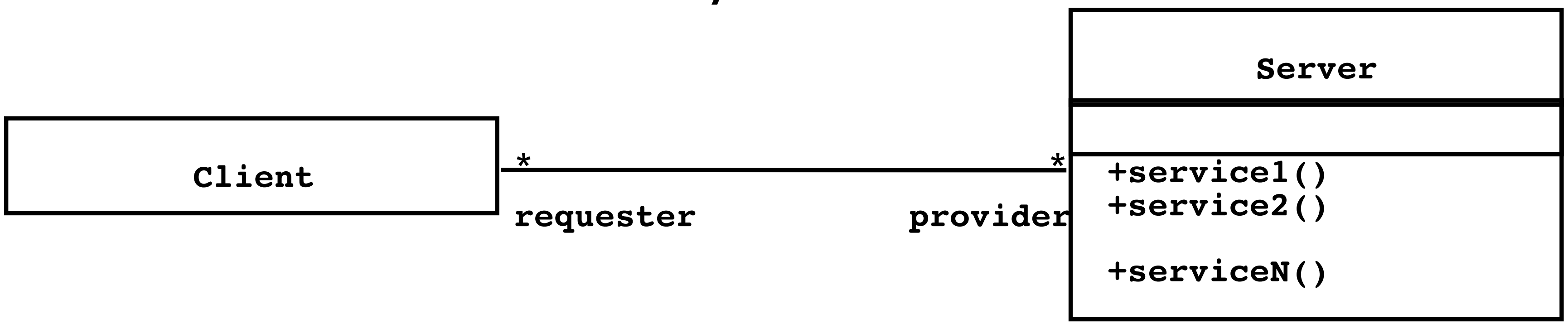
- ✓ Layered Architectural Style
  - ✓ Service-Oriented Architecture (SOA)
- Client/Server
- Peer-to-Peer
- Three-tier, Four-tier Architecture
- Repository
  - Blackboard
- Model-View-Controller
- Pipes and Filters

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

Client/Server Architectural Style

- Special case of the Layered 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.

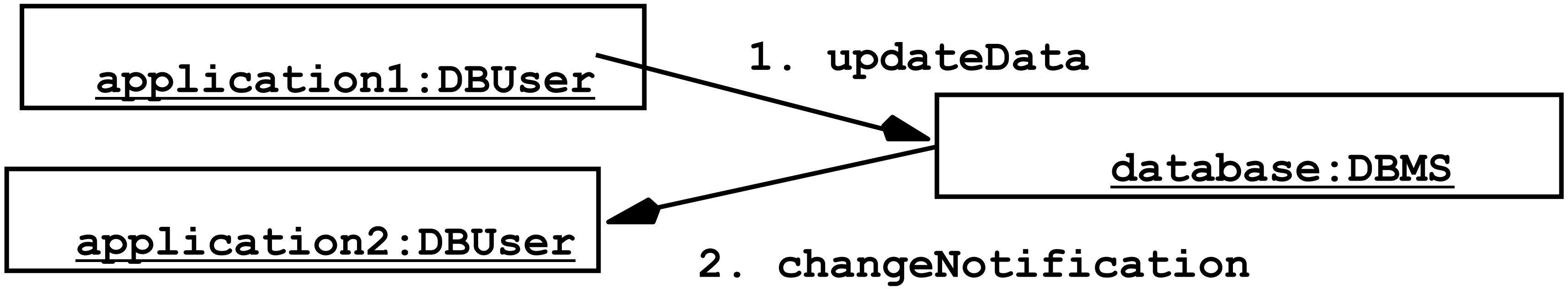


Design Goals for Client/Server Architectures

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 Architectural Style

"Clients can be servers and servers can be clients"

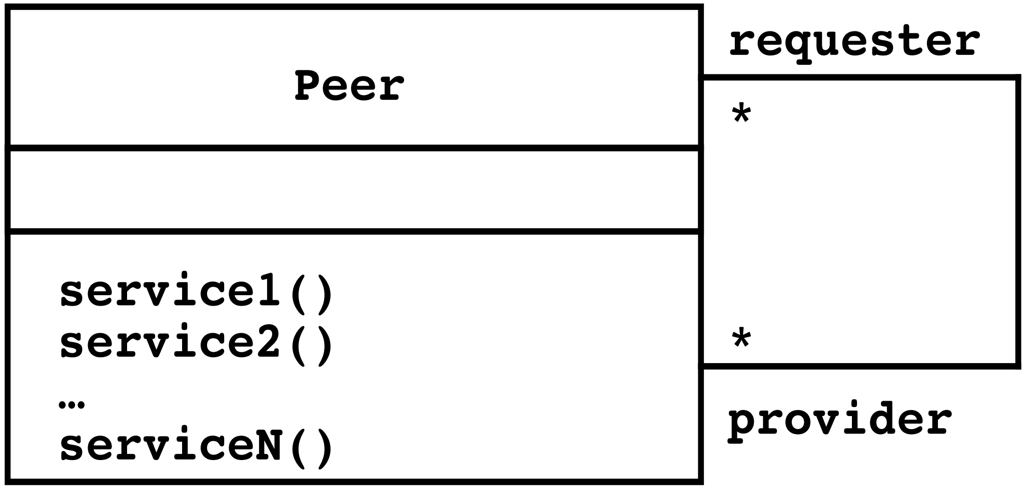
Introduction a new abstraction: Peer

"Clients and servers can be both peers"

How do we model this statement? With Inheritance?

Proposal 1: "A peer can be either a client or a server"

Proposal 2: "A peer can be a client as well as a server".



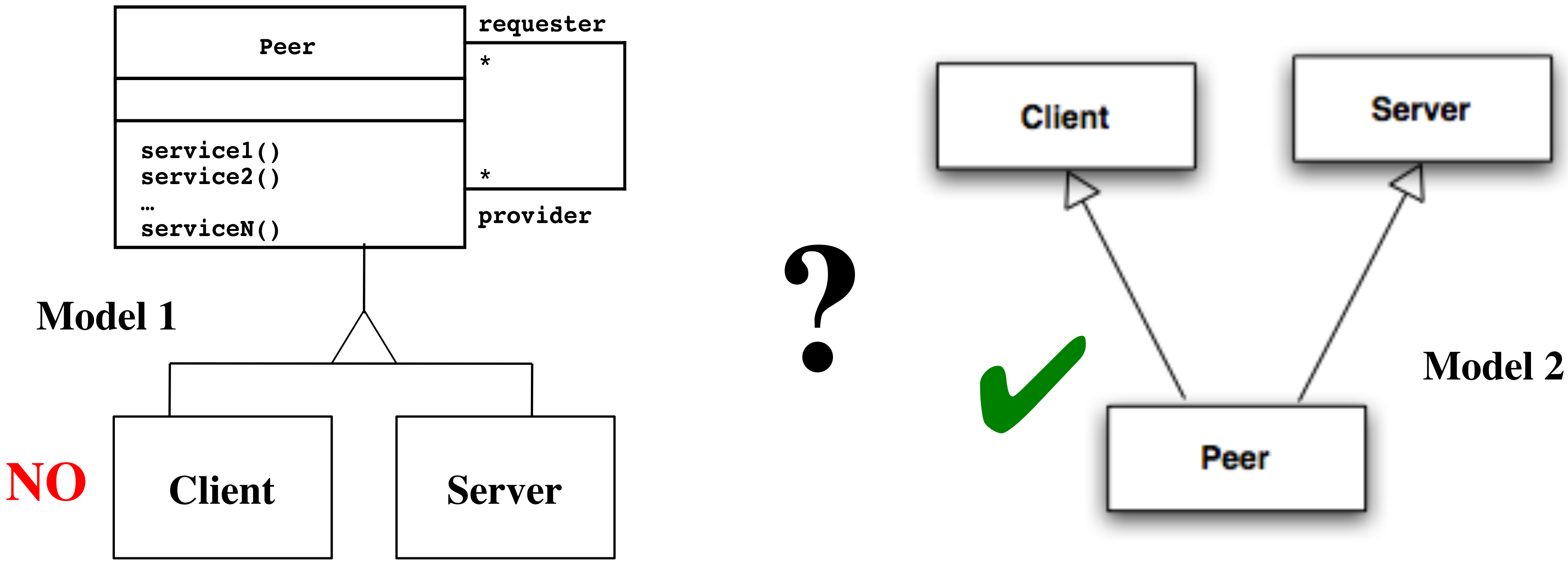
Relationship Client/Server & Peer-to-Peer

Problem statement "Clients can be servers and servers can be clients"

Which model is correct?

Model 1: "A peer can be either a client or a server"

Model 2: "A peer can be a client as well as a server"



3-Layer-Architectural Style
3-Tier Architecture

Definition: 3-Layered Architectural 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.

Example of a 3-Layered Architectural Style

- Three-Layered 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.

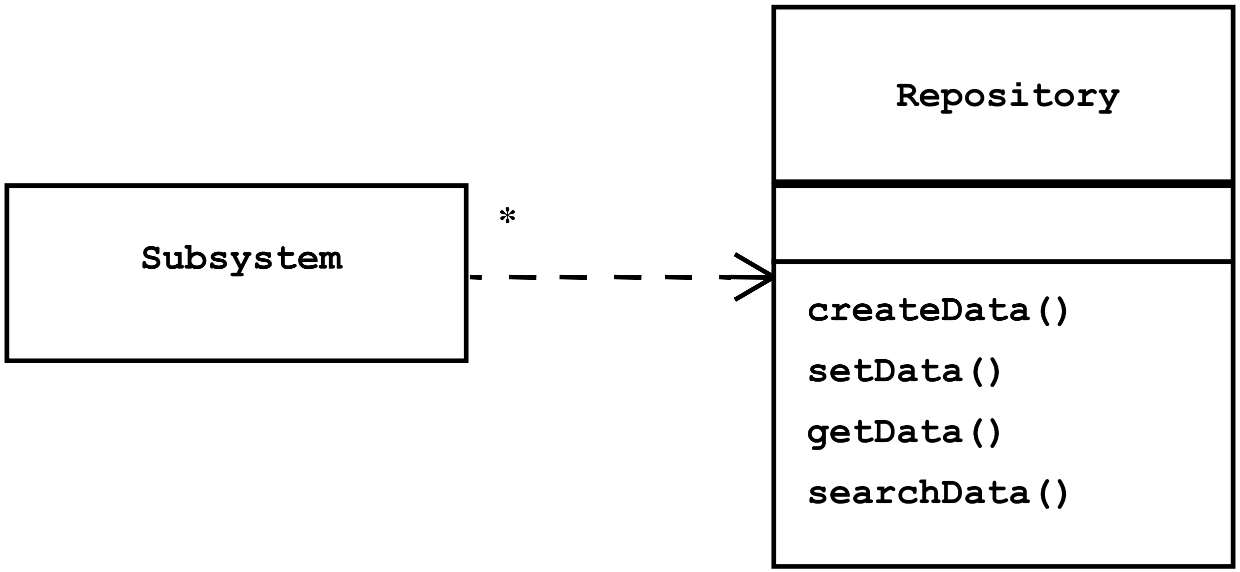
Example of a 4-Layered Architectural Style

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

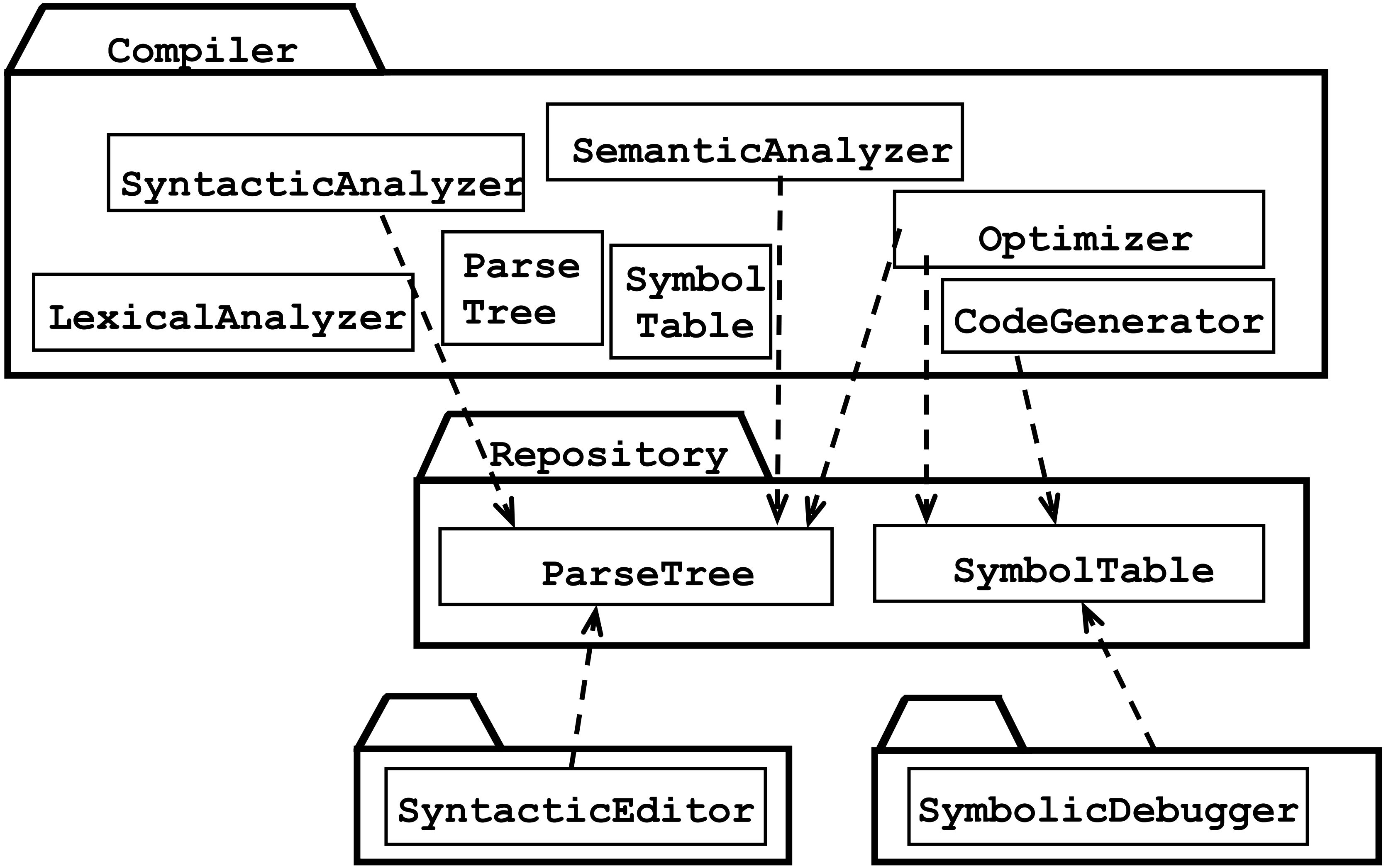
1. The Web Browser, providing the user interface
2. A Web Server, serving static HTML requests
3. An Application Server, providing session management (for example the contents of an electronic shopping cart) and processing of dynamic HTML requests
4. A back end Database, that manages and provides access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

Repository Architectural Style

- The basic idea behind this architectural style is to support a collection of independent programs that work cooperatively on a common data structure called the repository
- Subsystems access and modify data from the repository. The subsystems are loosely coupled (they interact only through the repository).



Repository Architecture Example: Incremental Development Environment (IDE)



Repository architectures: when and why

- Repository architectures are **well suited for applications with constantly changing complex data processing tasks**.
- Once a central repository is well defined, we can **easily add new services** in the form of additional subsystems.
- The main **disadvantage** of repository systems is that the **central repository** can quickly **become a bottleneck**, both from a performance aspect and a modifiability aspect.
- The **coupling** between each subsystem and the repository **is high**, thus making it difficult to change the repository without having an impact on all subsystems.

Model-View-Controller Architectural Style

- Problem: In systems with high coupling changes to the user interface (boundary objects) 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: Decoupling! The model-view-controller (MVC) style decouples data access (entity objects) and data presentation (boundary objects)
  - Views: Subsystems containing boundary objects
  - Model: Subsystem with entity objects
  - Controller: Subsystem mediating between Views (data presentation) and Models (data access).

Model-View-Controller Architectural Style

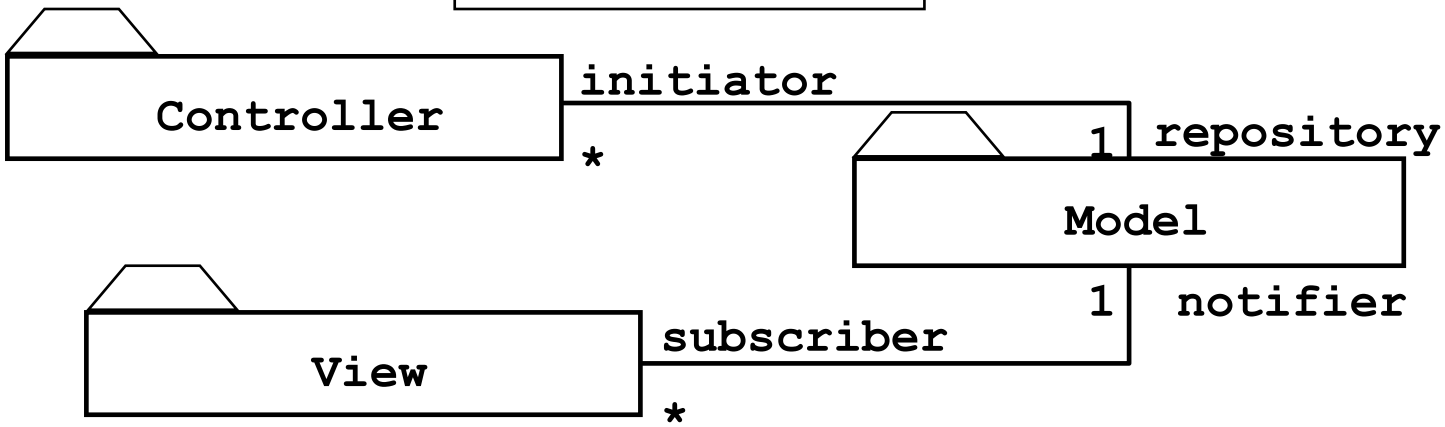
- Subsystems are classified into 3 different types

  Model subsystem: Responsible for application domain knowledge

  View subsystem: Responsible for displaying information to the user

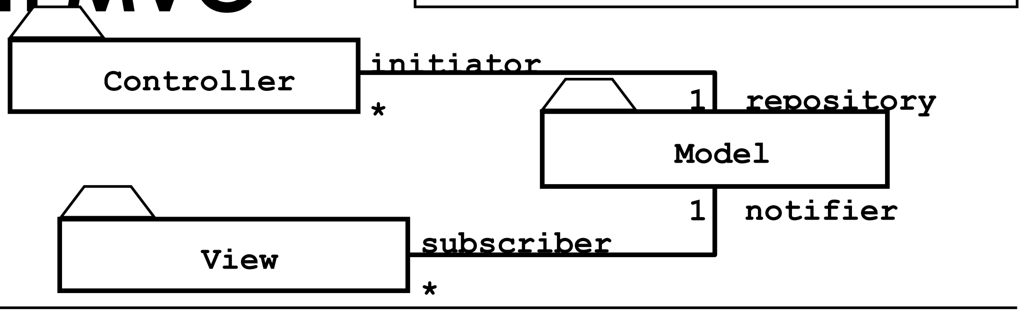
  Controller subsystem: Responsible for interacting with the user and notifying views of changes in the model

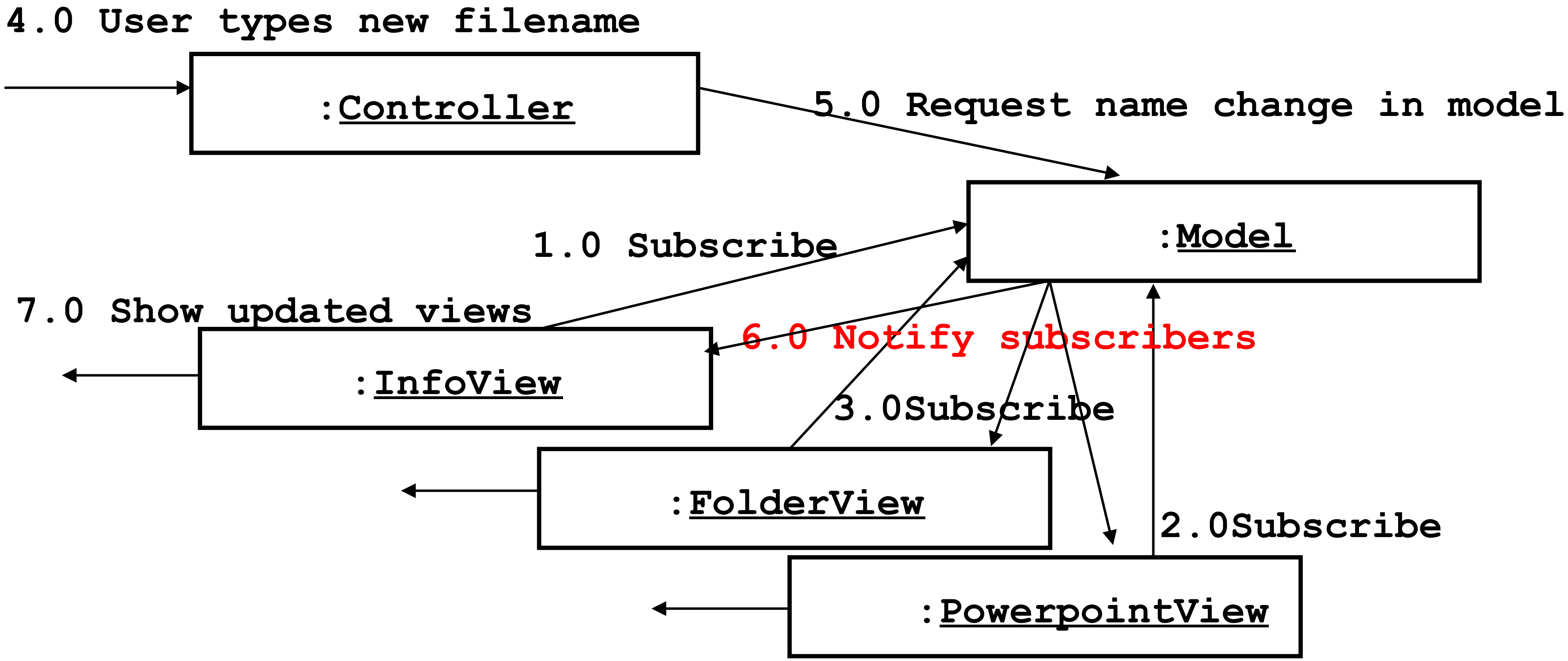
Class Diagram



Example: Modeling the Sequence of Events in MVC

UML Class Diagram





UML Communication Diagram

Review: UML Communication Diagram

- A Communication Diagram 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
    - Communication 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 number and placed near the link the message is sent over
- Reading a communication diagram involves starting at message 1.0, and following the messages from object to object.

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
- 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.

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

Summary

- System Design
  - Reduces the gap between problem and existing machine
- Design Goals
  - Describe important system qualities and values against which alternative designs are evaluated (design-tradeoffs)
  - Additional nonfunctional requirements found at design time
- Subsystem Decomposition
  - Decomposes the overall system into manageable part by using the principles of cohesion and coherence
- Architectural Style
  - A pattern for a subsystem decomposition: All kind of layer styles (C/S, SOA, n-Tier), Repository, MVC, Pipes&Filters
- Software architecture
  - An instance of an architectural style.

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
- 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
- Frank Buschmann et al:
  - Pattern-Oriented Software Architecture, Vol 1: A System of Patterns, Wiley, 1996.

Backup Slides

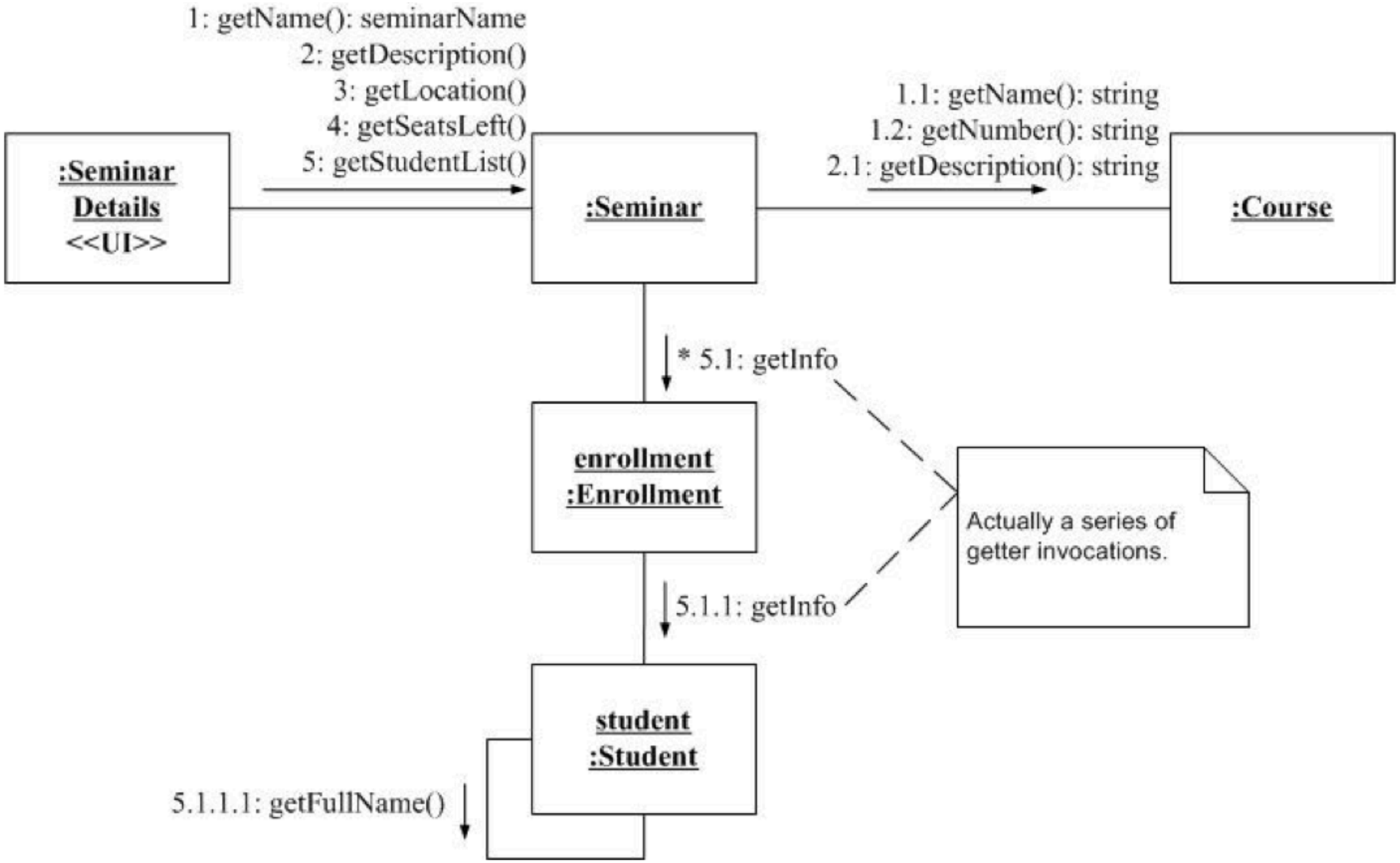
Excursion: Communication vs Collaboration Diagrams

- UML is a living language
- Communication diagram is a new term in UML 2.0
- In UML 1.x they used to be called collaboration diagrams
  - You find this term still in many books and in articles in the web
- We use the terms synonomously

Communication Diagrams vs Class Diagrams vs Sequence Diagrams

- Difference between communication diagrams and class diagrams:
  - Association labels, roles and multiplicities are not shown in communication diagrams. Associations between objects denote messages depicted as a labeled arrows that indicate the direction of the message, using a notation similar to that used on sequence diagrams
- Difference between communication diagrams and sequence diagrams:
  - Both focus on the message flow between objects
  - Sequence diagrams are good at illustrating the event flow over time. They can show temporal relationsships such as causality and temporal concurrencies
  - Communication diagrams focus on the structural view of the communication between objects, not the timing issues.

Communication Diagram: An Example



Exercise (Also Possible as a Homework)

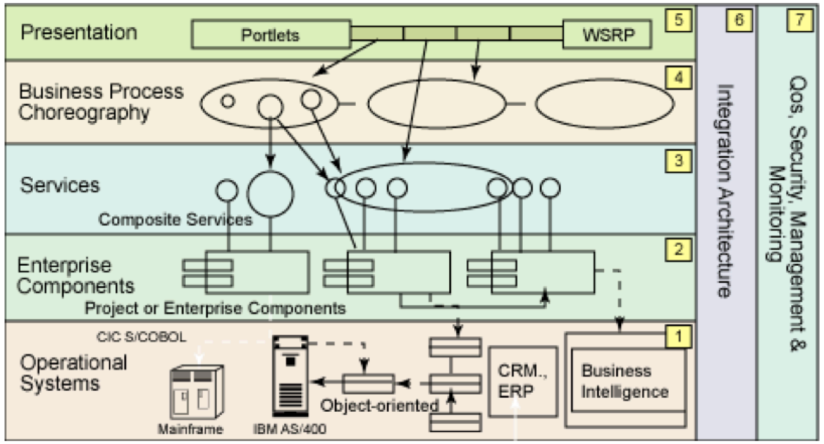
- Assume the communication diagram from the previous slide is the only information you have about a system, which is currently paper-based
- You are asked to digitize the system. Reverse engineer the system model by performing these tasks:

1. Write the problem statement
   - Use your application domain knowledge to describe the functional and nonfunctional requirements
2. Identify the object model
   - Draw the corresponding class diagram
   - Add Associations: find multiplicies and role names
   - Identify inheritance and aggregation associations
3. Complete the dynamic model:
   - Draw the corresponding sequence diagram
   - Identify actors, events and messages
4. Identify the functional model
   - Identify the actors and use cases.

5 System Design steps to create a layered architecture

1. Define the abstraction criterion
   - Also called “the conceptual distance to the existing system (“platform”). Examples of abstraction criteria:
     - The degree of customization for a specific domain
     - The degree of conceptual complexity
2. Determine the number of abstraction levels
   - Each abstraction layer corresponds to one layer of the pattern
3. Name the layers and assign tasks to each of them
   - The task of the highest layer is the overall system task, as perceived by the client. The tasks of all the other layers are helper layers. (The lower layers provide the infrastructure needed by the higher layers)
4. Specify the services
   - Lower layers should be "slim‟, while higher layers can cover a broader spectrum of applicability. Also called the "inverted pyramid of reuse‟
5. Refine the layering
   - Iterate over steps 1 to 4.

SOA Layers



- **Layer 5: Access/Presentation layer**
  - Application layer. Not part of SOA, but increasingly important because technologies such as Web Services for Remote Portlets provide services at this level
- **Level 4: Business process choreography layer**
  - This layer provides compositions of services defined in layer 3. The composition acts as a single service offered to applications
- **Layer 3: Services layer**
  - All the services offered by the business are located in this layer. A service is a discoverable software component with an externalized service description. This service description is available for searching, binding, and invocation by a SOA higher layer
- **Layer 2: Enterprise components layer**
  - Provides the functionality of the legacy systems via adapters. Responsible for maintaining workload management, high-availability and load balancing
- **Layer 1: Operational systems layer**
  - Existing custom built or old applications that are still of business value, (called *legacy systems*). Examples: existing CRM and ERP applications.

SOA Architecture

The following description is taken from:

http://www.ibm.com/developerworks/webservices/library/ws-soa-design1/

„Level 6: Integration Architecture

This layer enables the integration of services through intelligent routing, protocol mediation, and other transformation mechanisms, often described as the ESB (see Resources). The Web Services Description Language (WSDL) specifies a binding, which implies a location where the service is provided. On the other hand, an ESB provides a location transparent mechanism for integration

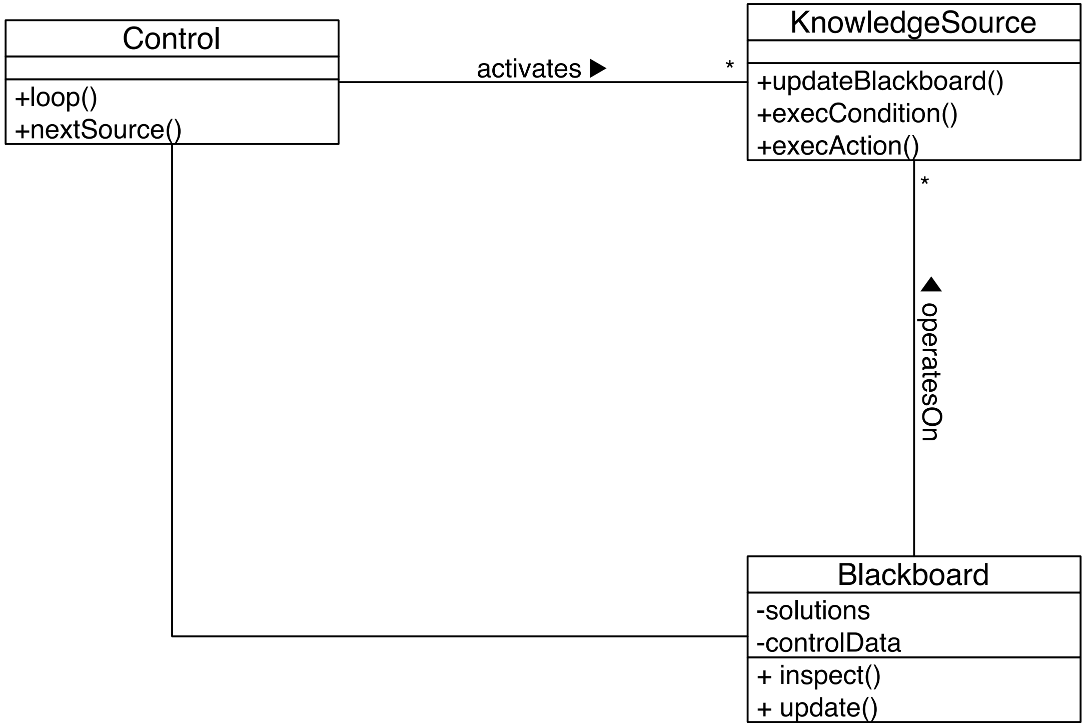
Level 7: QoS

This layer provides the capabilities required to monitor, manage, and maintain QoS such as security, performance, and availability. This is a background process background processes through sense-and-respond mechanisms and tools that monitor the health of SOA applications, including the all important standards implementations of WS-Management and other relevant protocols and standards that implement quality of service for a SOA."

Question to the Previous Slide

- Is Integration Architecture a good term for a layer?
- Are these layers? If yes, how should they be drawn? If not, why not?

Blackboard Architectural Pattern



- The blackboard is the repository for the problem to be solved, partial solutions and new information
- The knowledge sources read anything that is placed on the black-board and place newly generated information on it
- Control governs the flow of problemsolving activity in the system, in particular how the knowledge sources get notified of any new information put on the blackboard.

Synonyms:

Control: Supervisor
Knowledge Source: Specialist, Expert
Blackboard: Knowledge Sharing Area.

Historic of Blackboard Style

- The blackboard architectural styel was initially used in the Hearsay II speech recognition system for recognizing sentences from a vocabulary of 1200 words (First called the blackboard architecture)
- In Hearsay II, hypotheses about the sentence were kept in different datastructures, so-called levels, in the blackboard (solutions in the blackboard pattern)

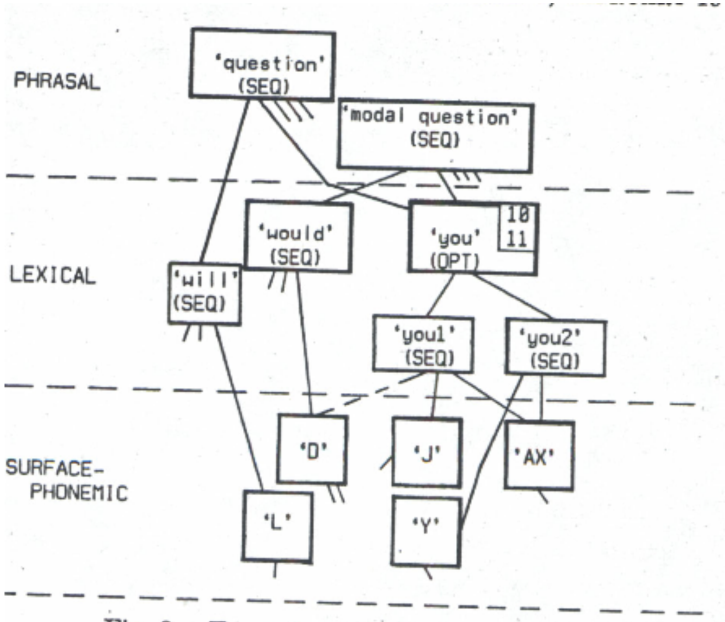
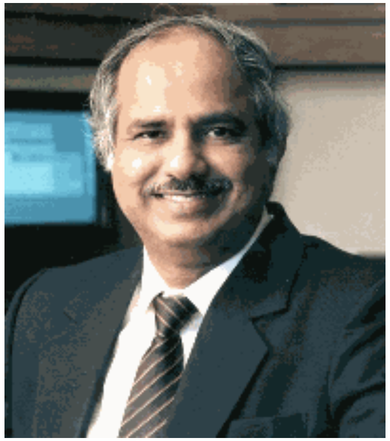


Fig. 3. Example of the data structure.

V. Lesser, R. Fennell, L. Erman and R. Reddy (1975)



Raj Reddy, *1937,
Carnegie Mellon University
- Major contributions in speech recognition (Hearsay II, Harpy), vision understanding, robotics, machine learning
- Founding Director of
  - the Robotics Institute,
  - the HCI Institute,
  - the Center for Machine Learning

1994: Turing Award (with Ed Feigenbaum).

Knowledge Sources in Hearsay II

- Segment Classifier (Acoustic expert)
  - Divides the waveform - represented as a se
    of parameters - into acoustic segments
- Phone Synthesizer
  - Generates elements at the phonetic level
- Word Candidate Generator
  - Uses the phonetic information to generate word hypotheses
- Syntactic Word Hypthesiser
  - Predicts new words at lexical level adjacent to previously generated generated words
- Phoneme Hypothesizer
  - Is activated whenever a word hypothesis is created which is not yet supported by a hypothesis at the surface-phonemic level
- Phone-Phoneme Synchronizer
  - Is triggered whenever a hypothesis is created at the phonetic or surface-phonemi level
- Syntactic parser
  - Uses the grammar for the input language to determine if a complete sentence can be assembled from the words.

The different data structures for hypotheses kept in the Blackboard (Solutions)

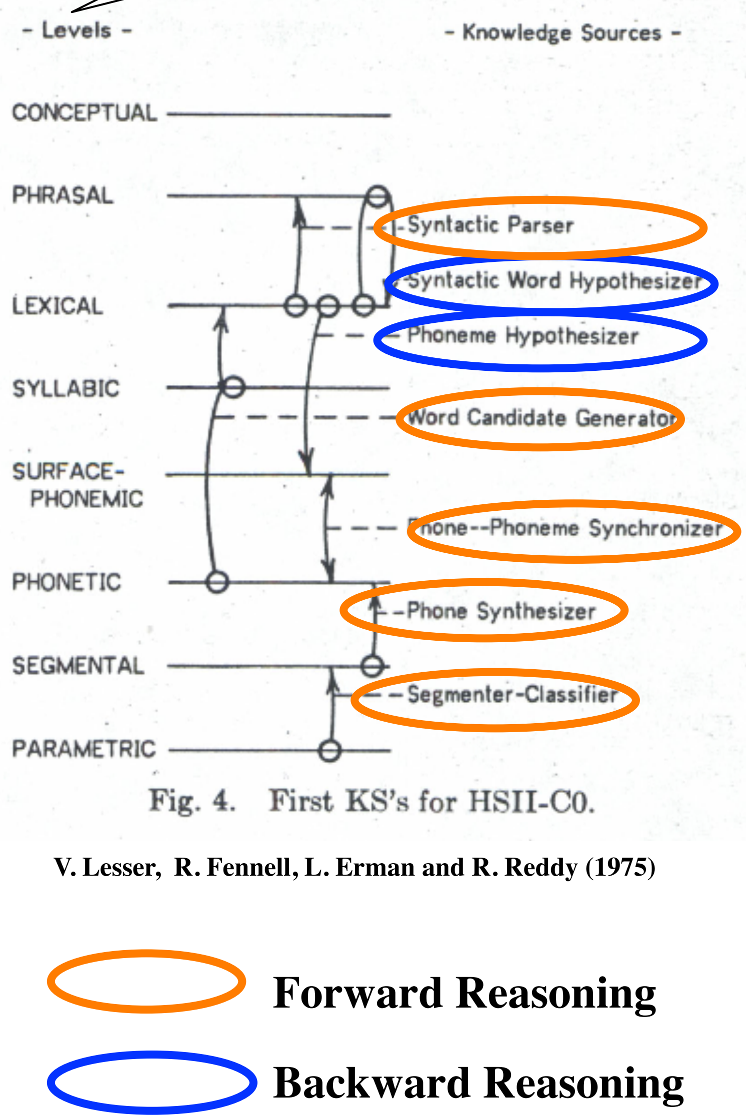


Fig. 4. First KS's for HSII-C0.

V. Lesser, R. Fennell, L. Erman and R. Reddy (1975)