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

System Design I: System Decomposition

Why is Design so Difficult?

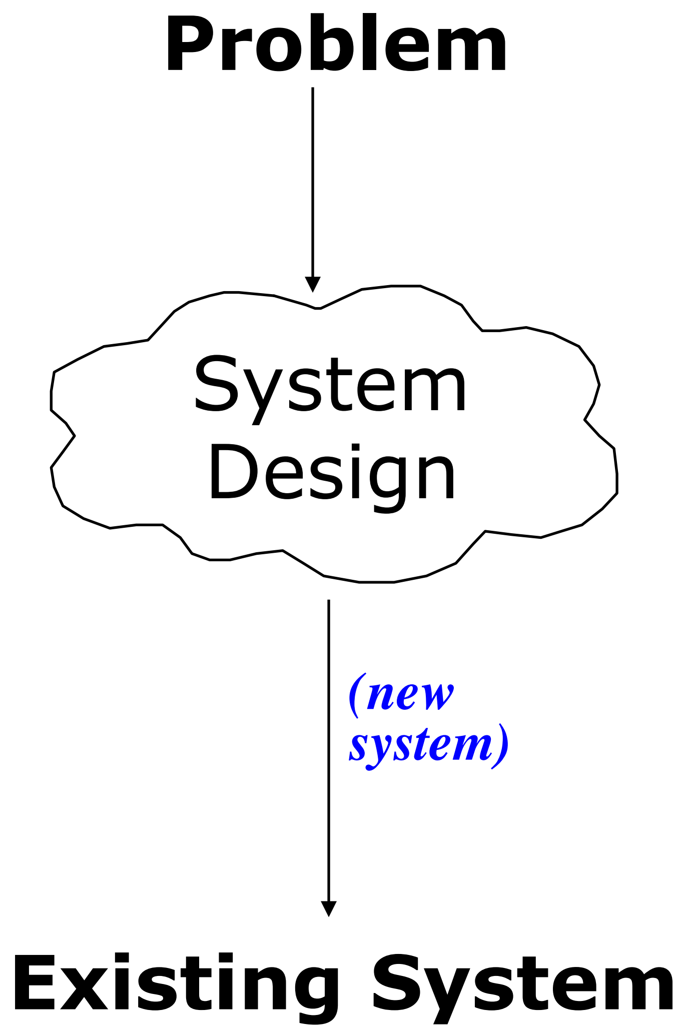
- Analysis: Focuses on the application domain
- Design: Focuses on the solution domain
  - The solution domain is changing very rapidly
    - Halftime knowledge in software engineering: About 3-5 years
    - Cost of hardware rapidly sinking
  - ➢ Design knowledge is a moving target

- 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

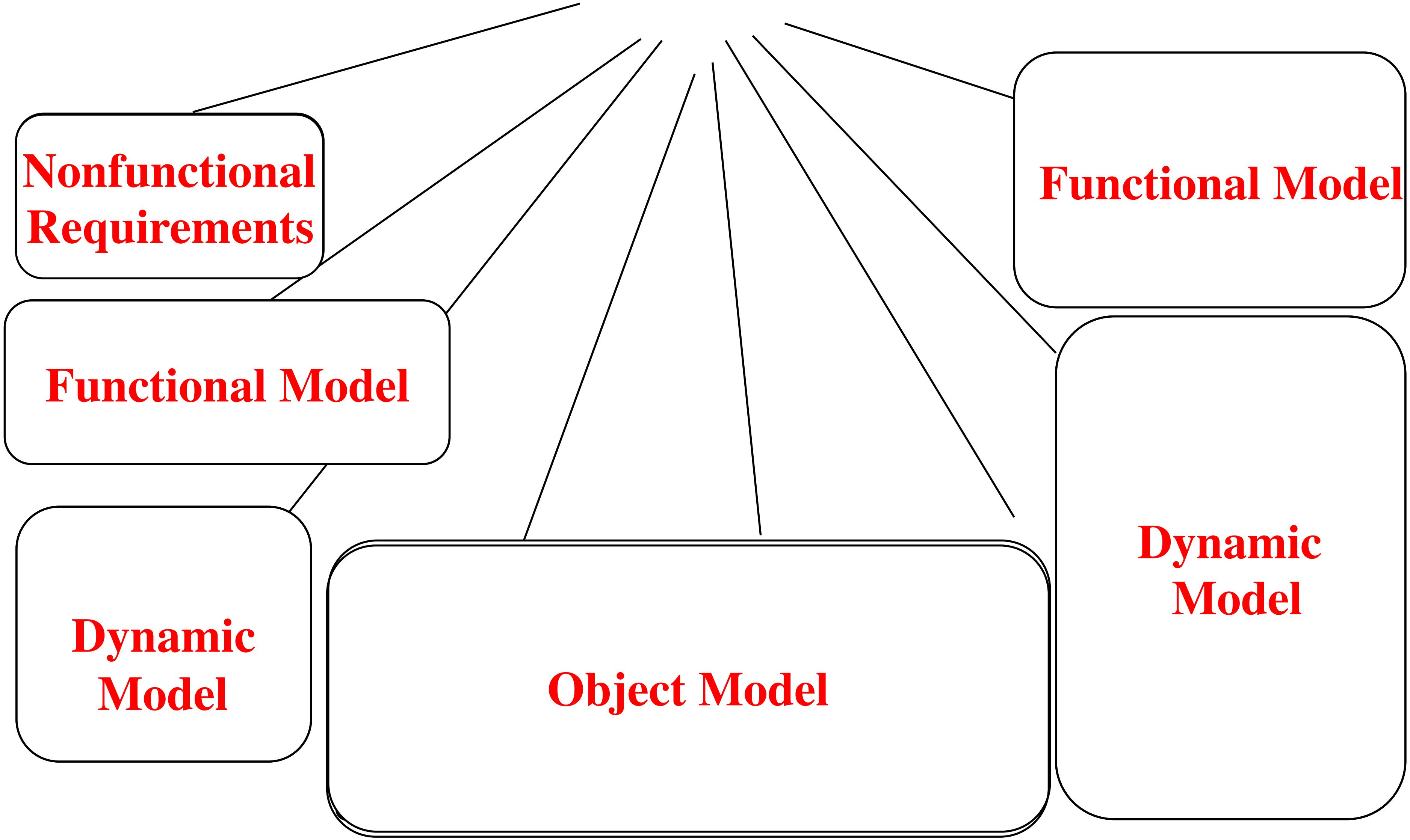
5. Persistent Data Management
- Storing Persistent Objects
- Filesystem vs Database

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

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

8. Boundary Conditions
- Initialization
- Termination
- Failure.

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
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Dynamic Model

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System Design Activities

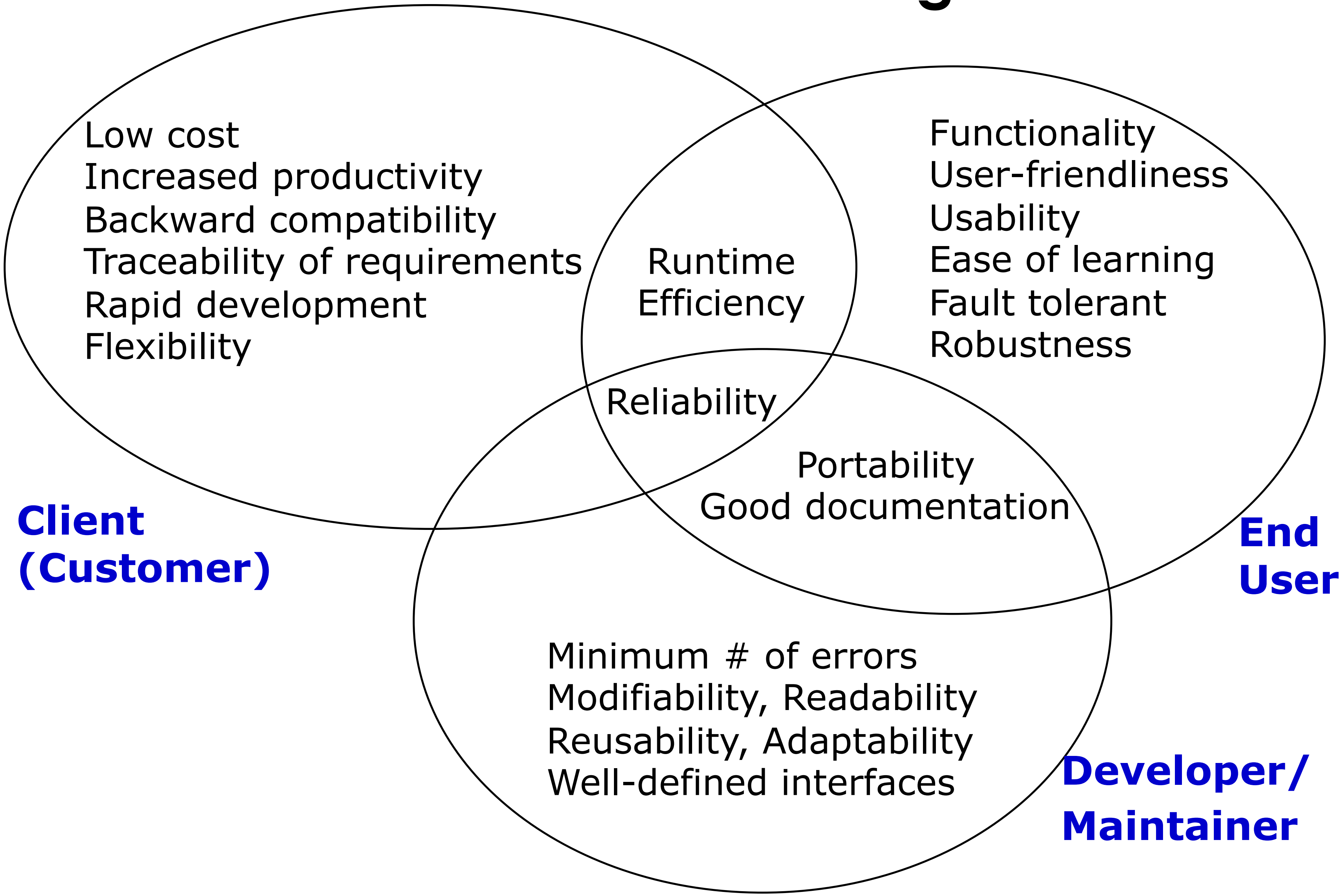
1) Design Goals
2) System Decomposition
3) Concurrency
4) Hardware/Software Mapping
5) Data Management
6) Global Resource Handling
7) Software Control
8) Boundary Conditions

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

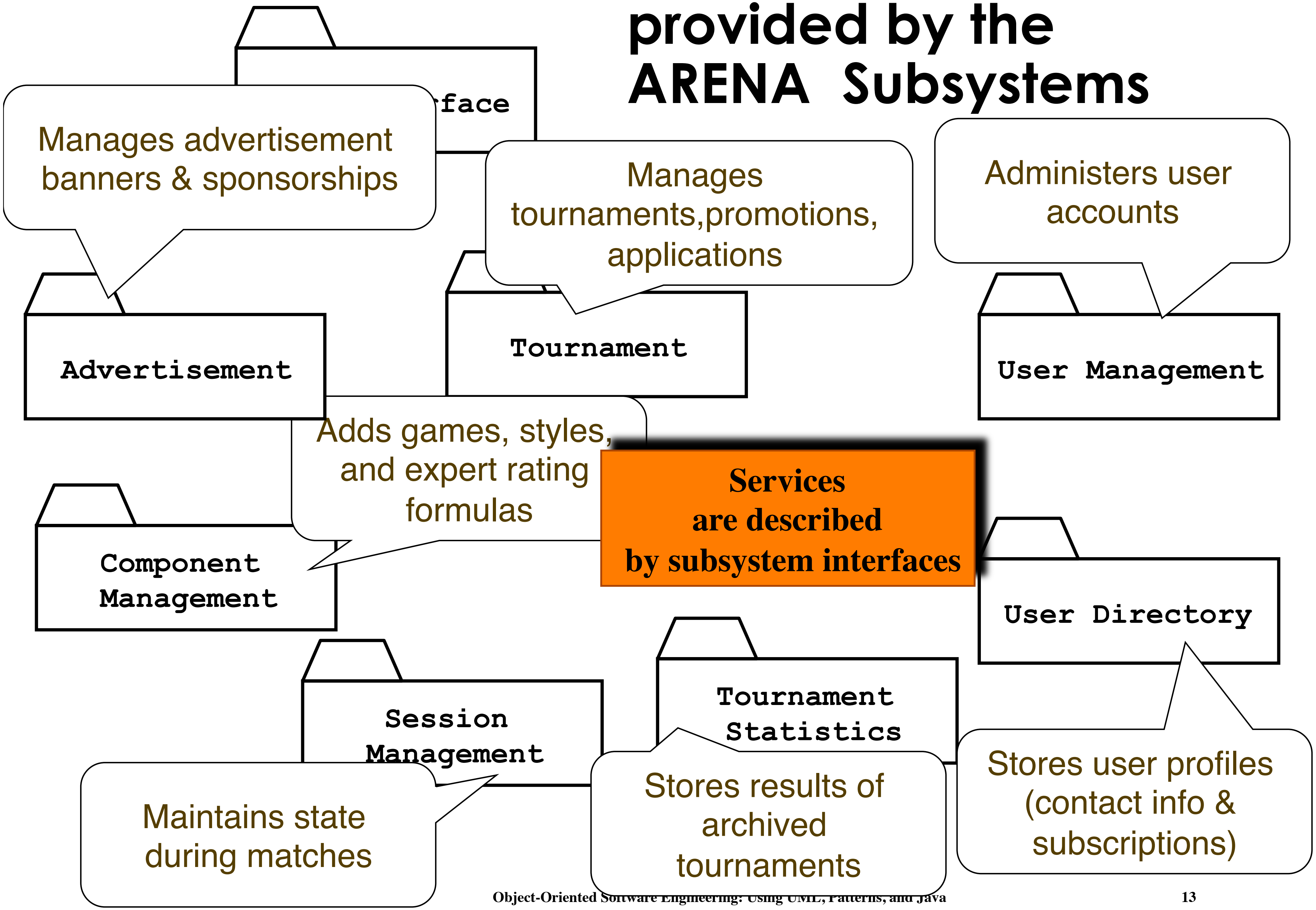
System Design Phases

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)
    - A service is usually realized by several (public) methods exposed by the classes of the same subsystem
  - 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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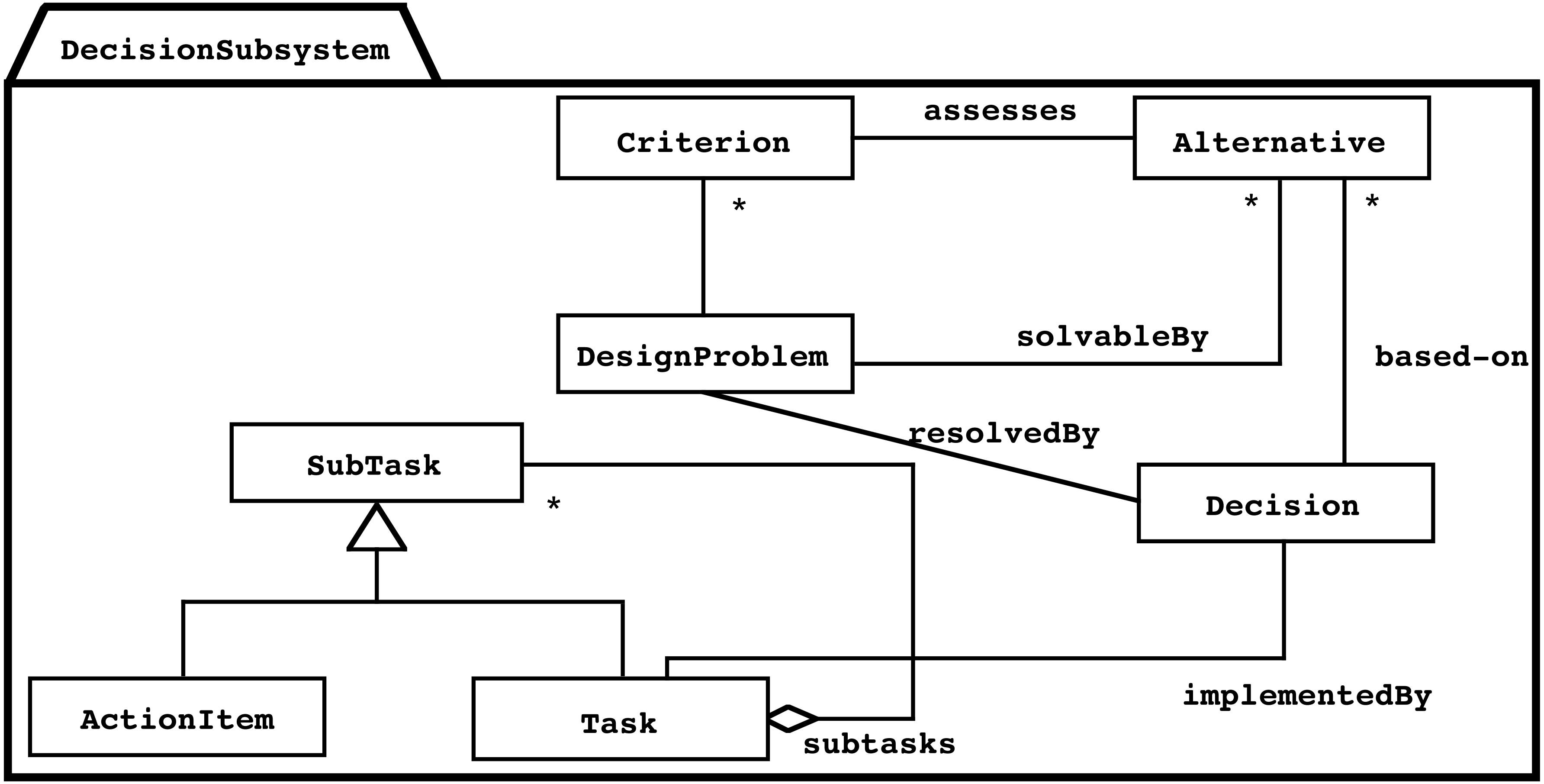
An example: the Decision tracking system

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`.

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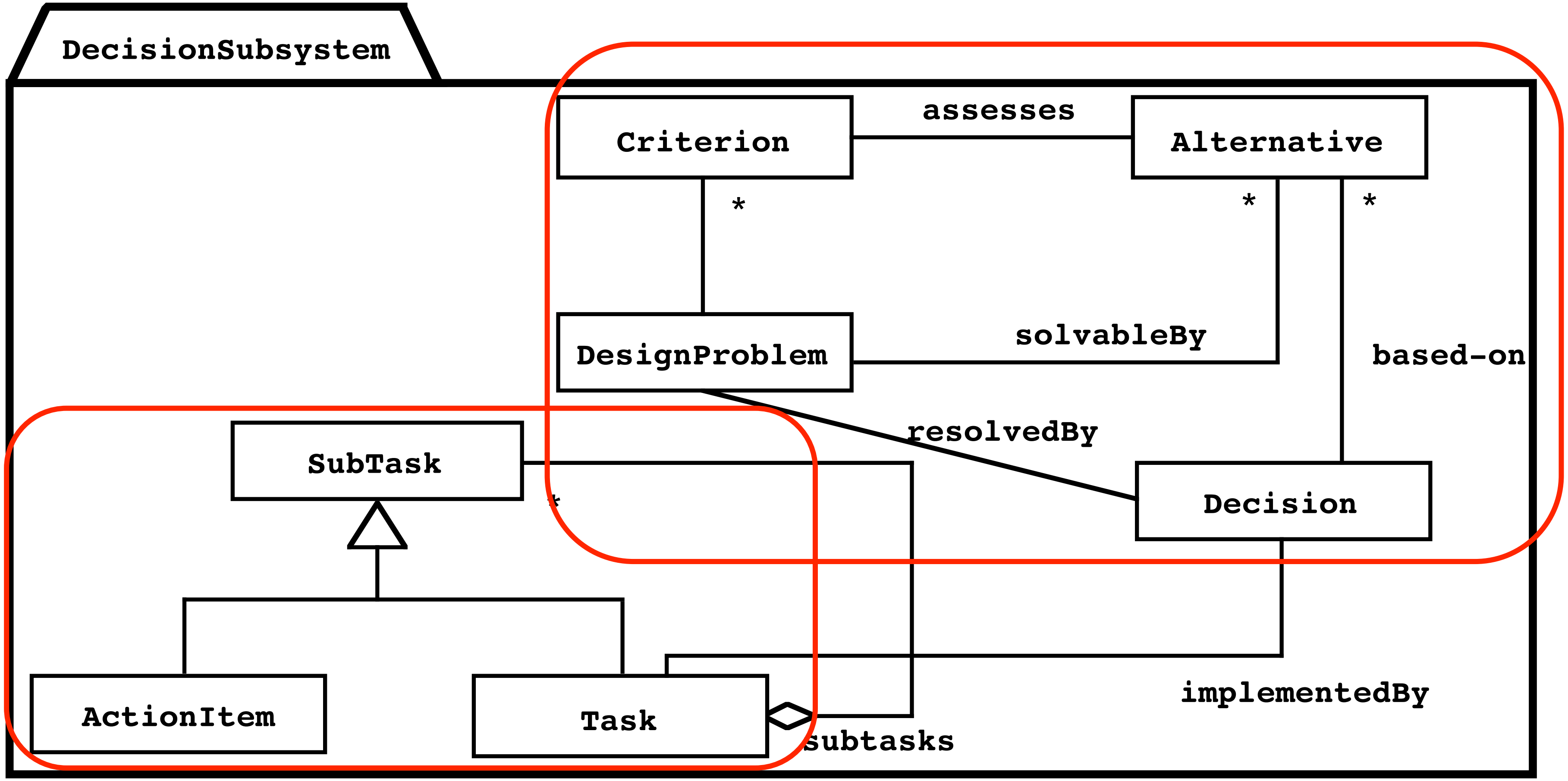

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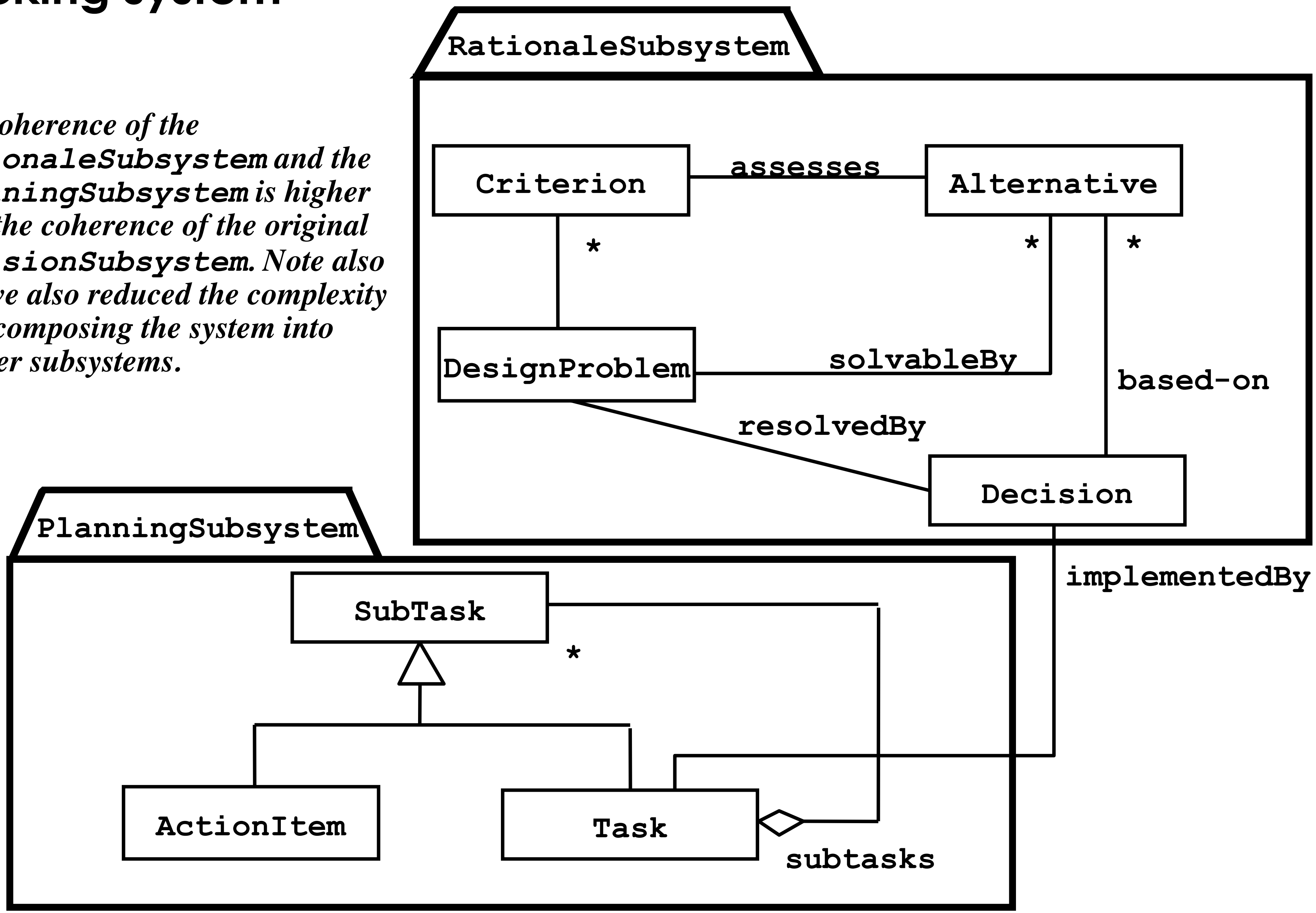
Alternative subsystem decomposition for the decision tracking system

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 high Coherence

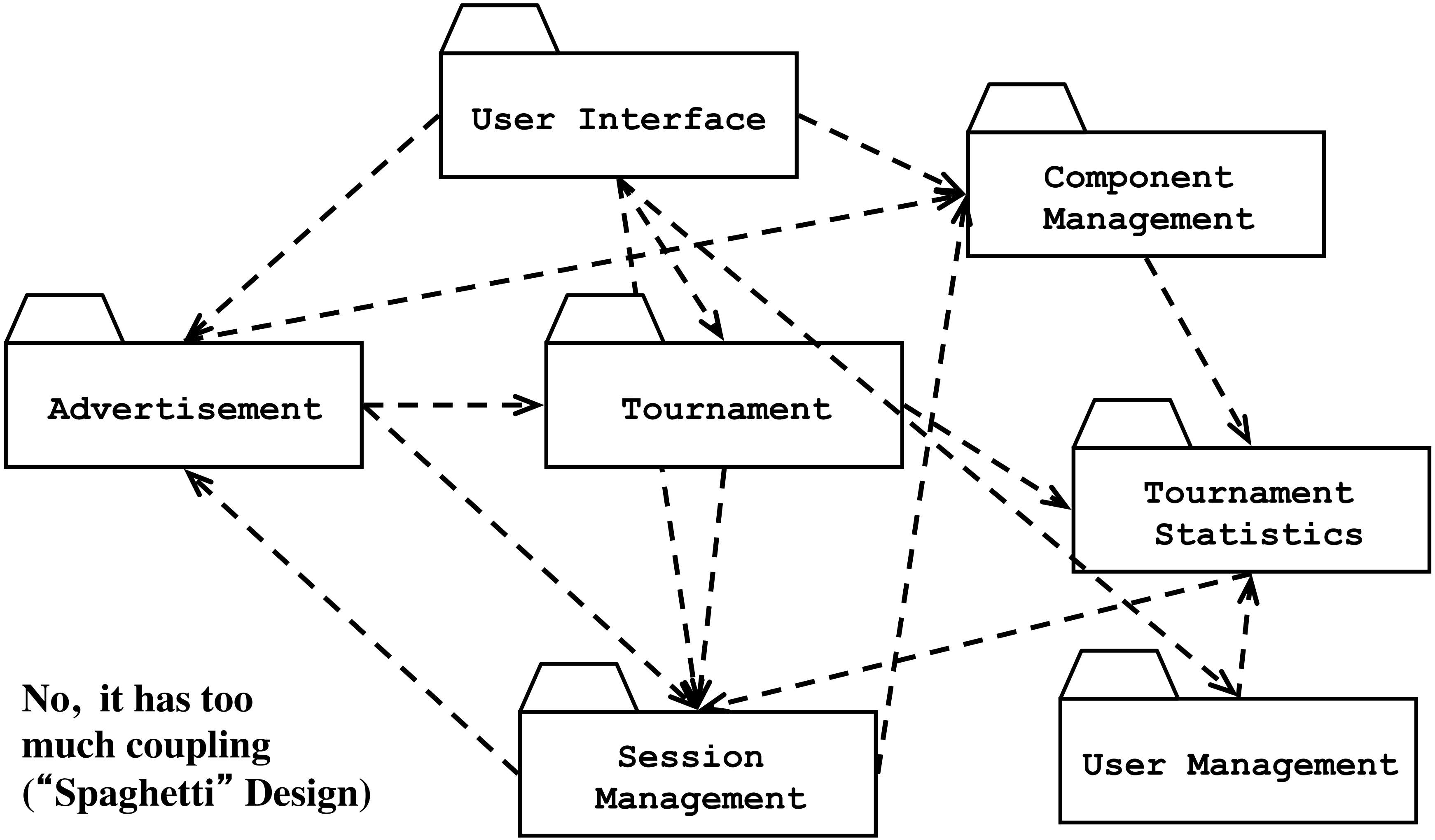
- High coherence can be achieved if most of the interaction is within subsystems, rather than across subsystem boundaries
- Questions to ask:
  - Does one subsystem always call another one for a specific service?
    - Yes: Consider moving them together into the same subystem.
  - Which of the subsystems 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)

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 *(Terms Definition)*

- 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

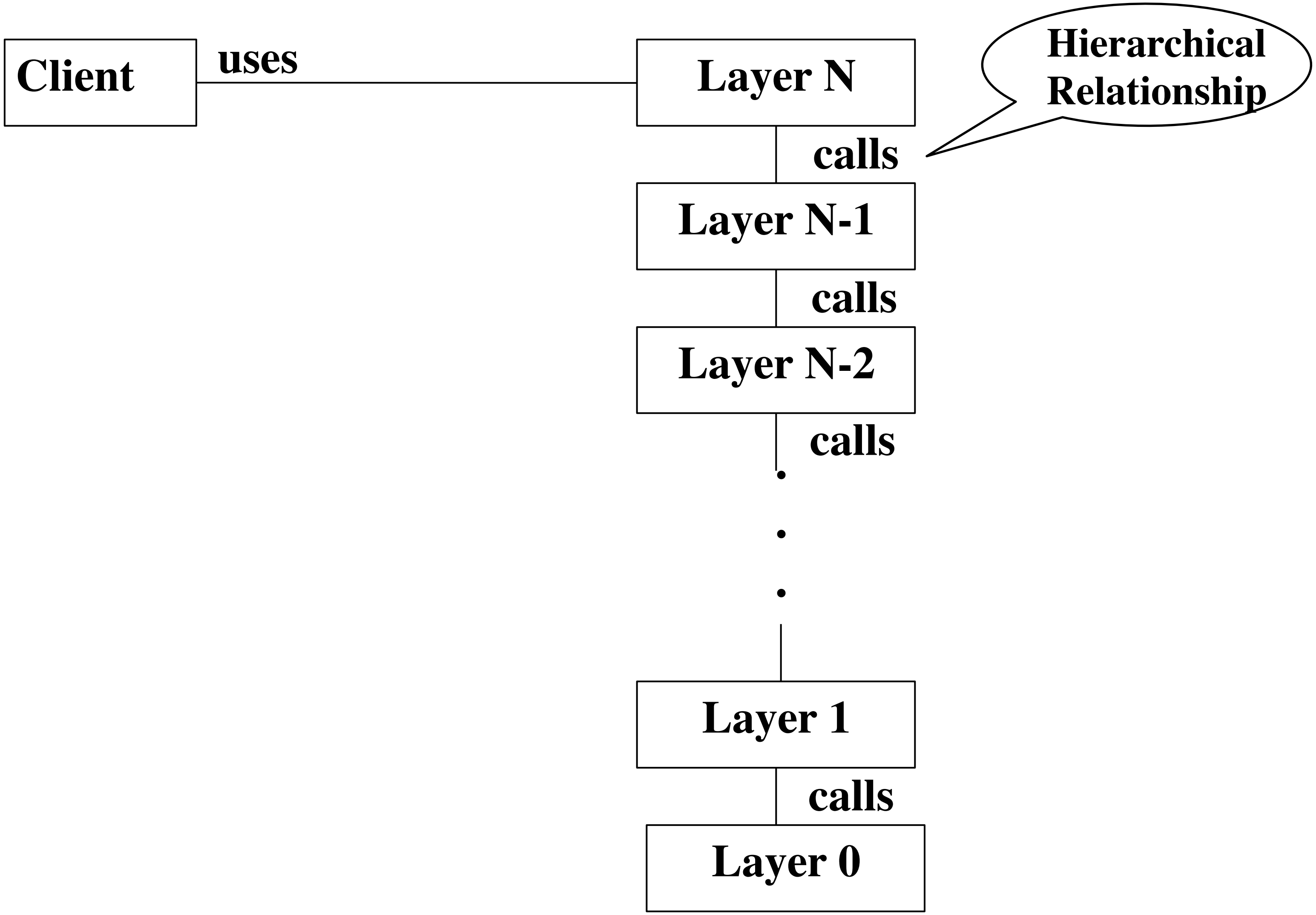
Partitions and Layers

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

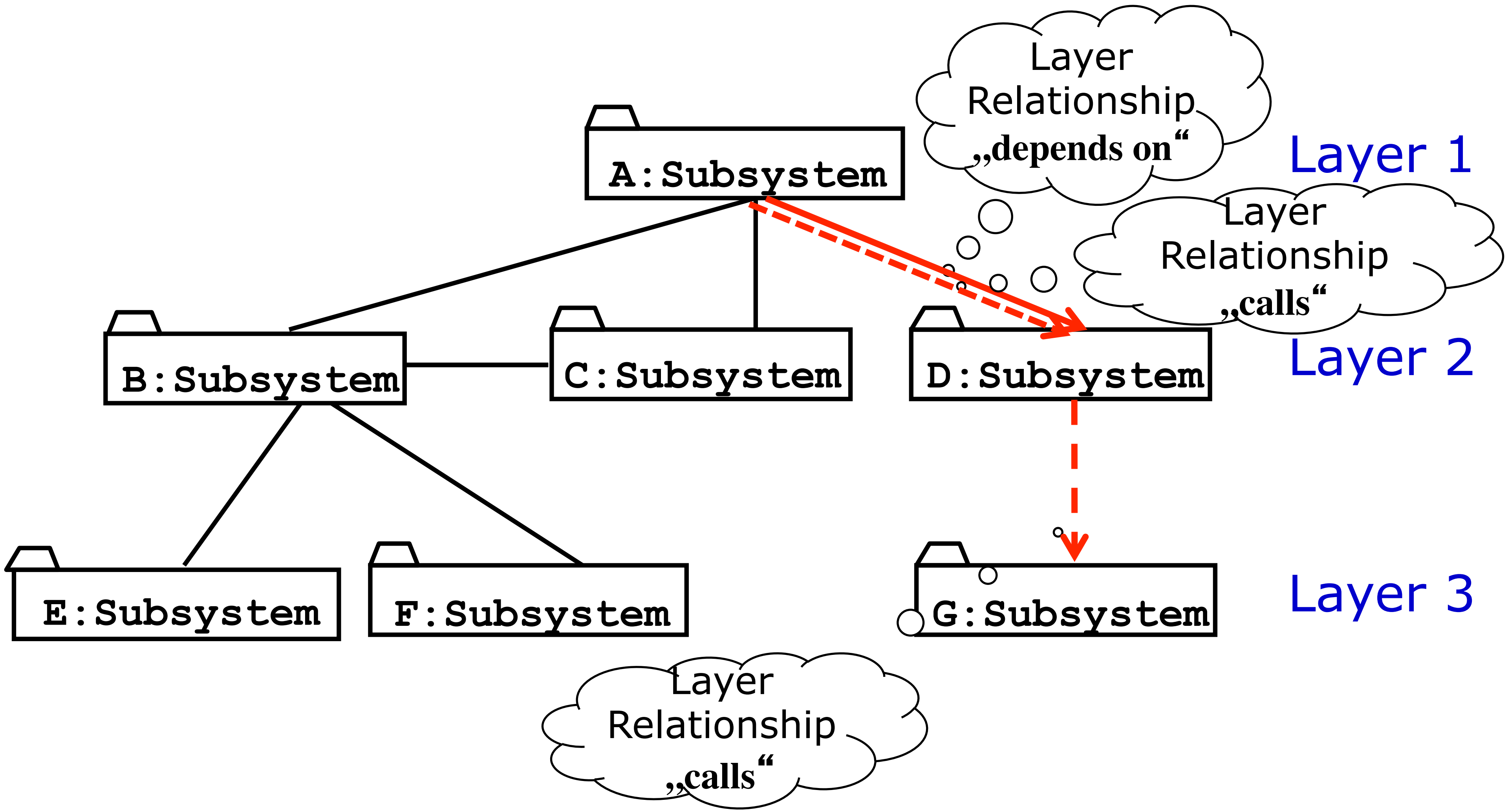
The Layered Architectural Style



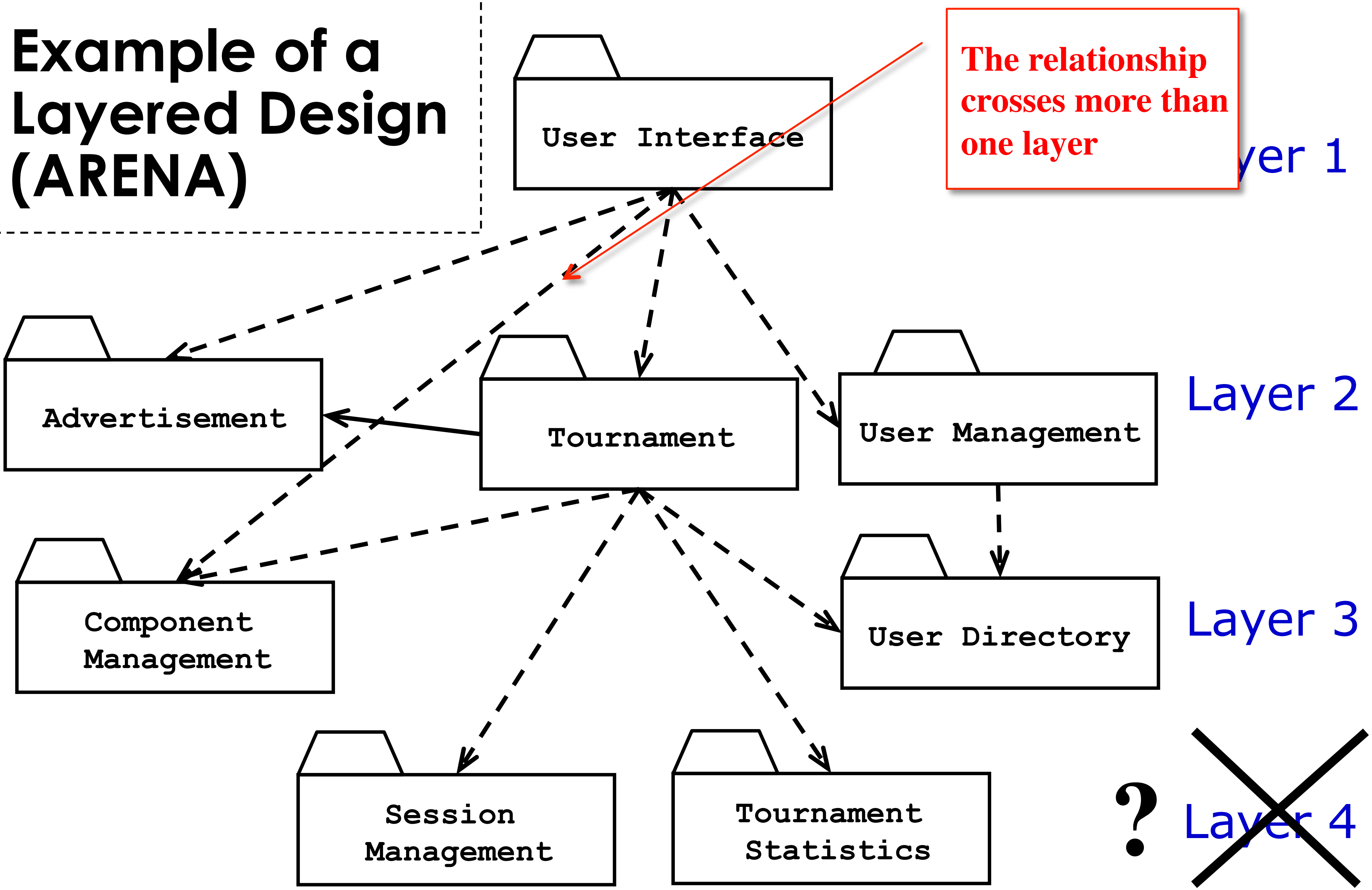
Hierarchical Relationships between Subsystems

- 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)

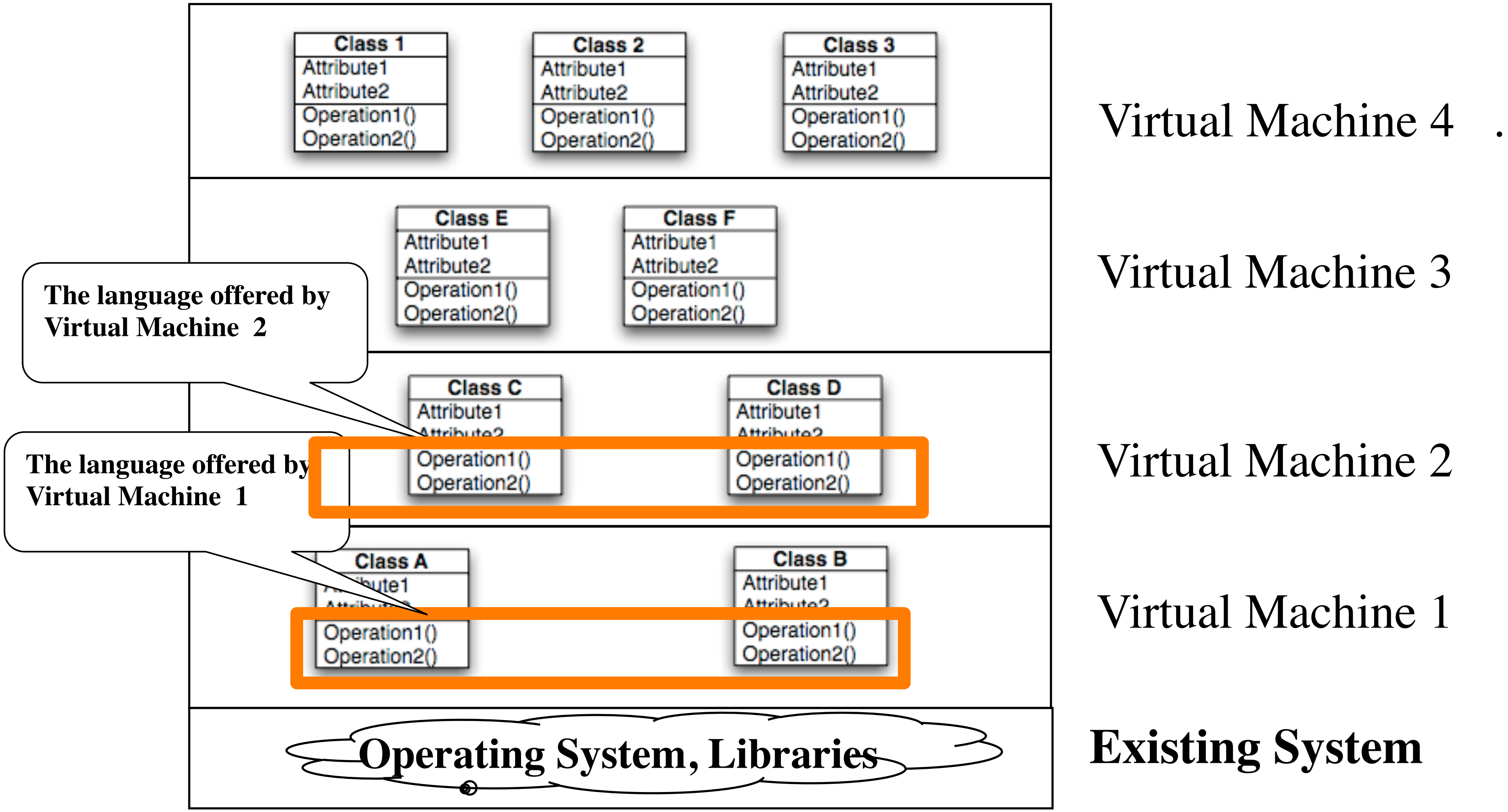


Virtual Machine

- 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

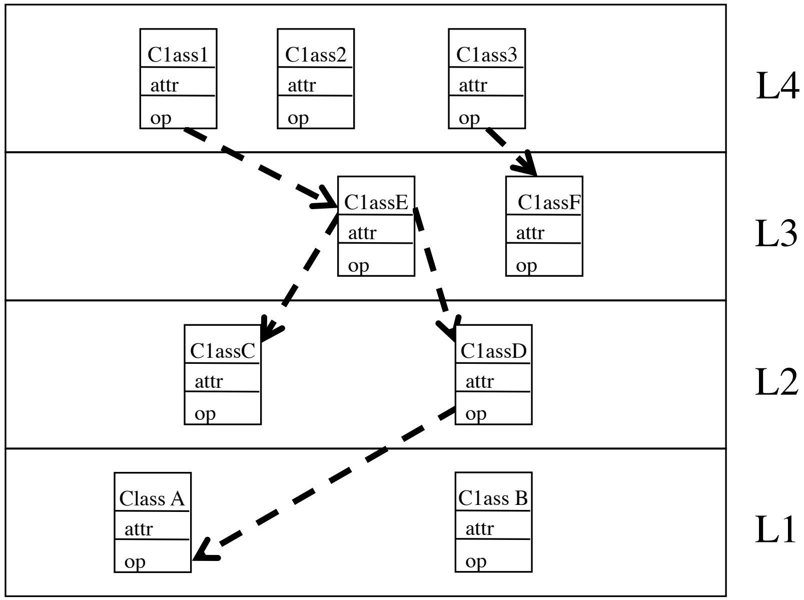
A system is a hierarchy of virtual machines, each using language primitives offered by the lower machines.



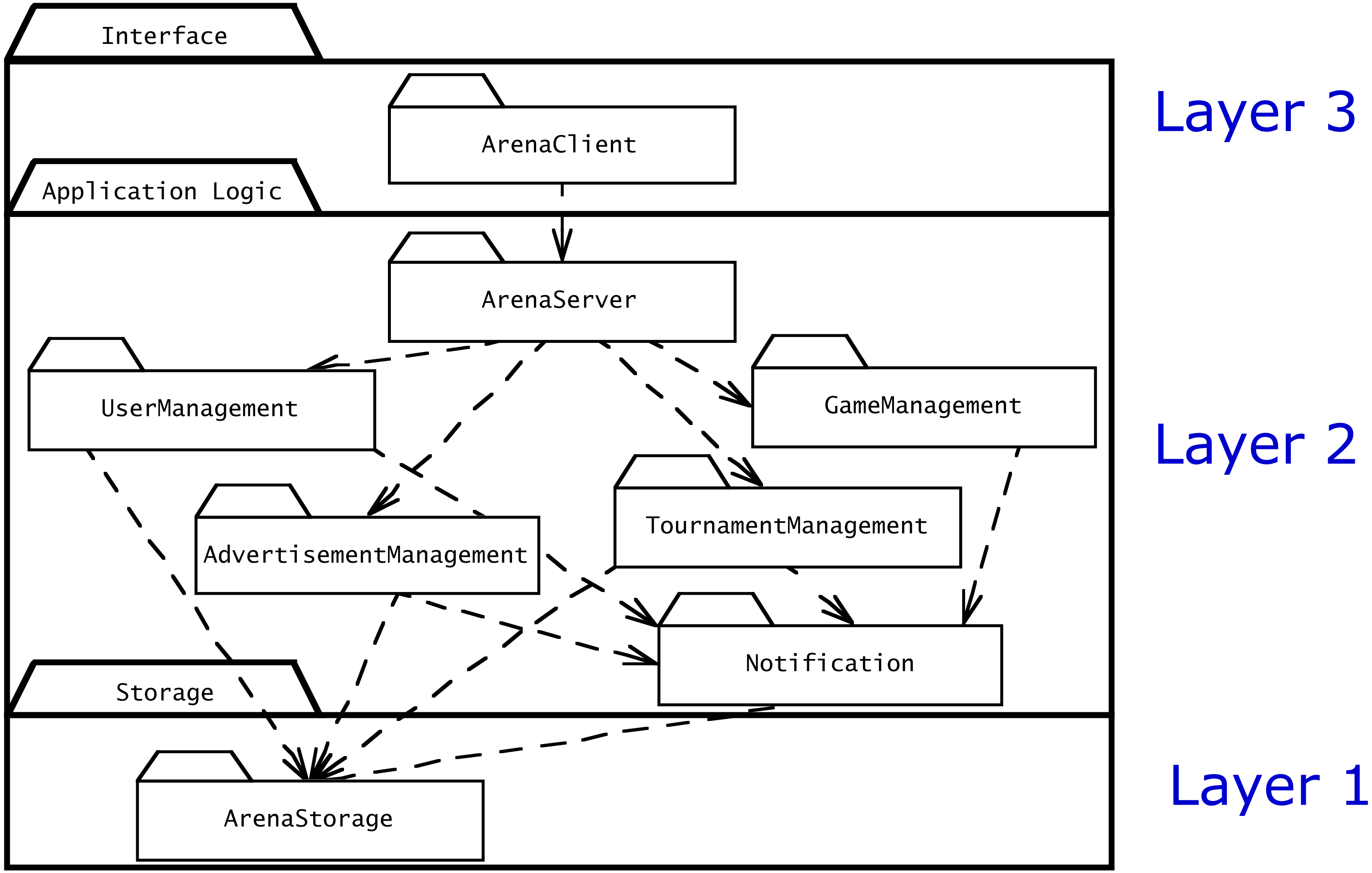
Closed Architecture (Opaque Layering)

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

Design goals: Maintainability, flexibility.



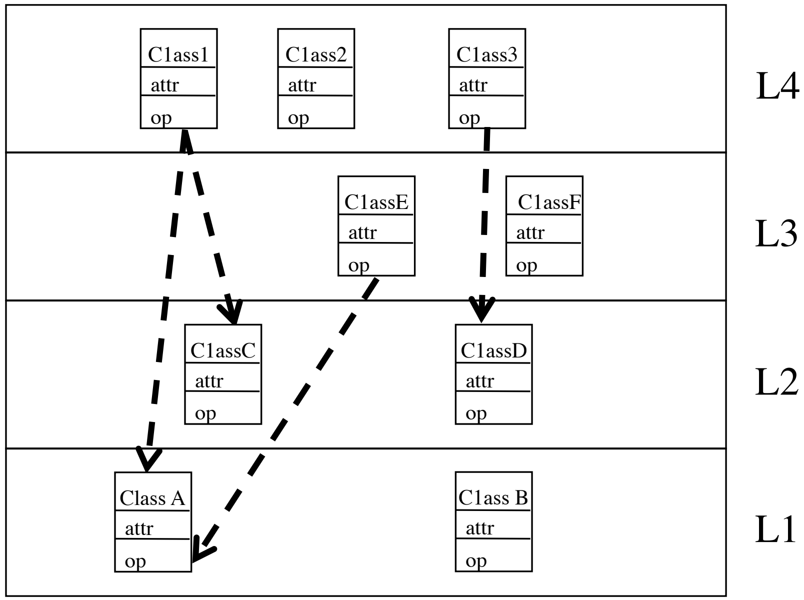
Opaque Layering in ARENA



Open Architecture (Transparent Layering)

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

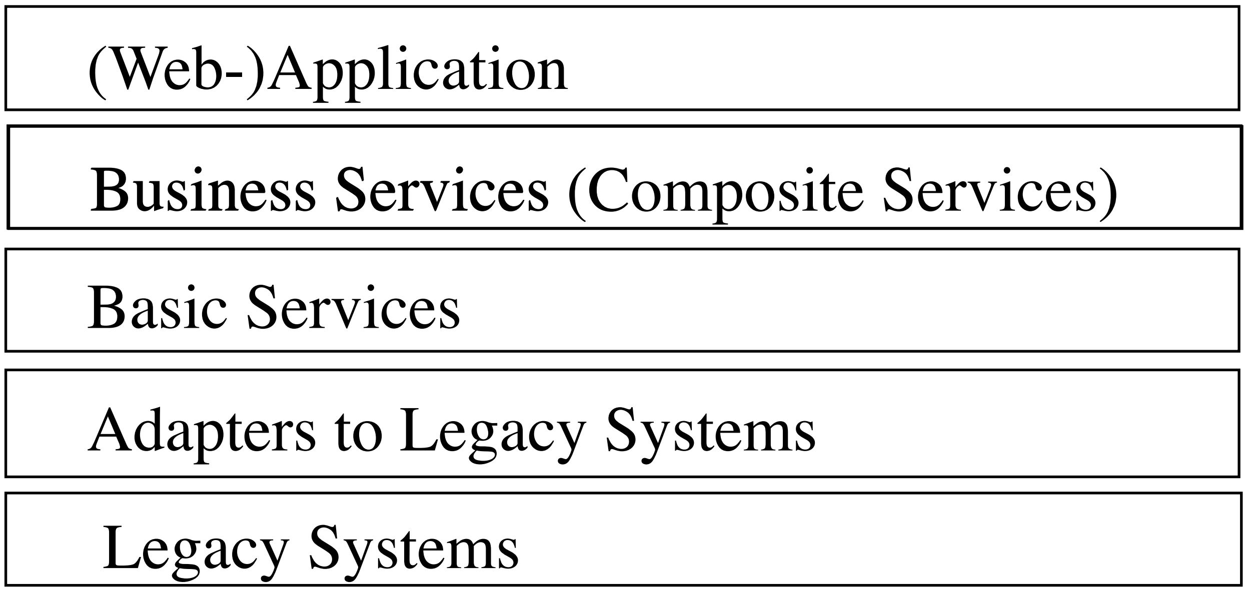
Design goal:
Runtime efficiency.



SOA is a Layered Architectural Style

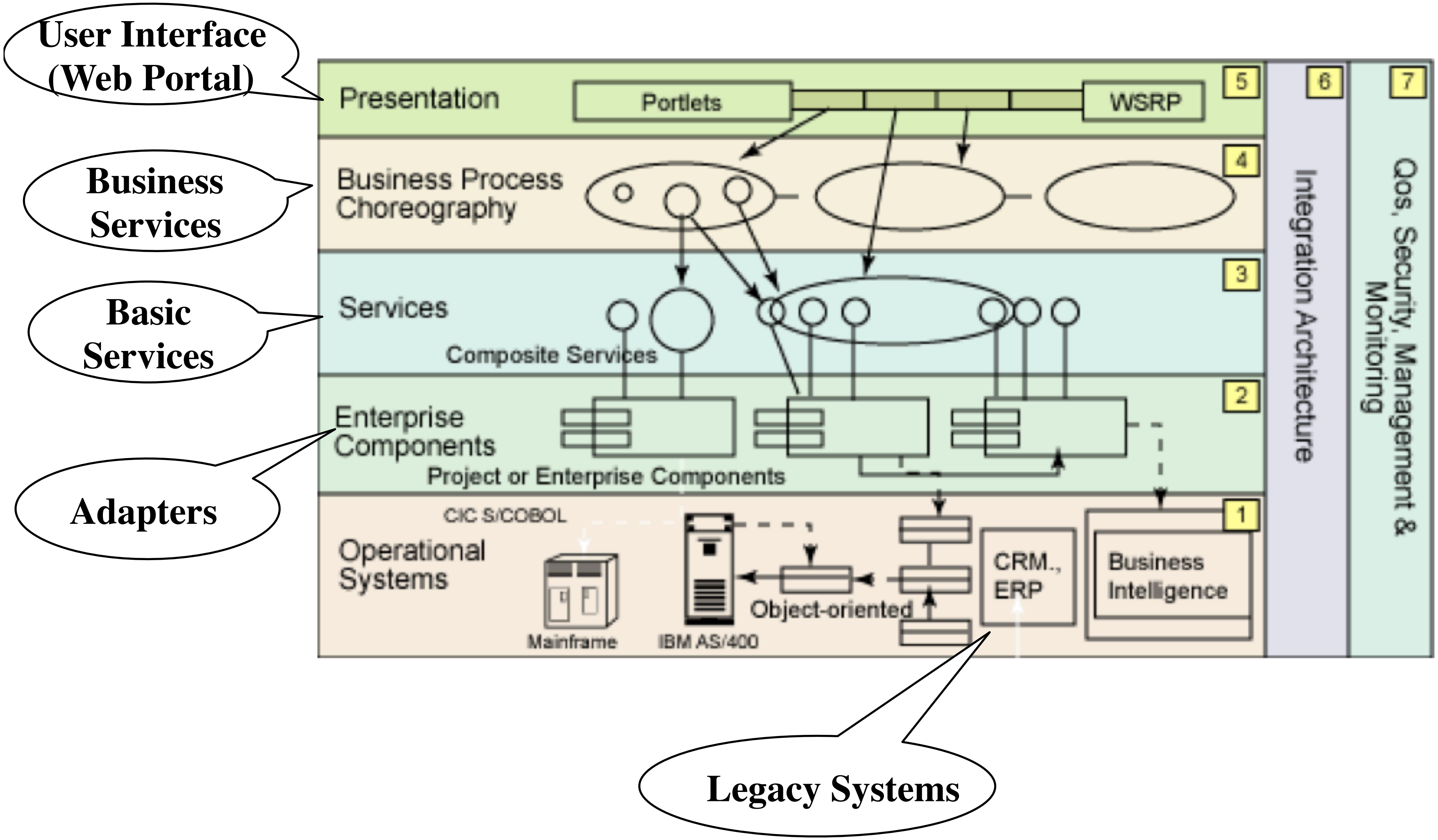
Service Oriented Architecture (SOA)

- 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

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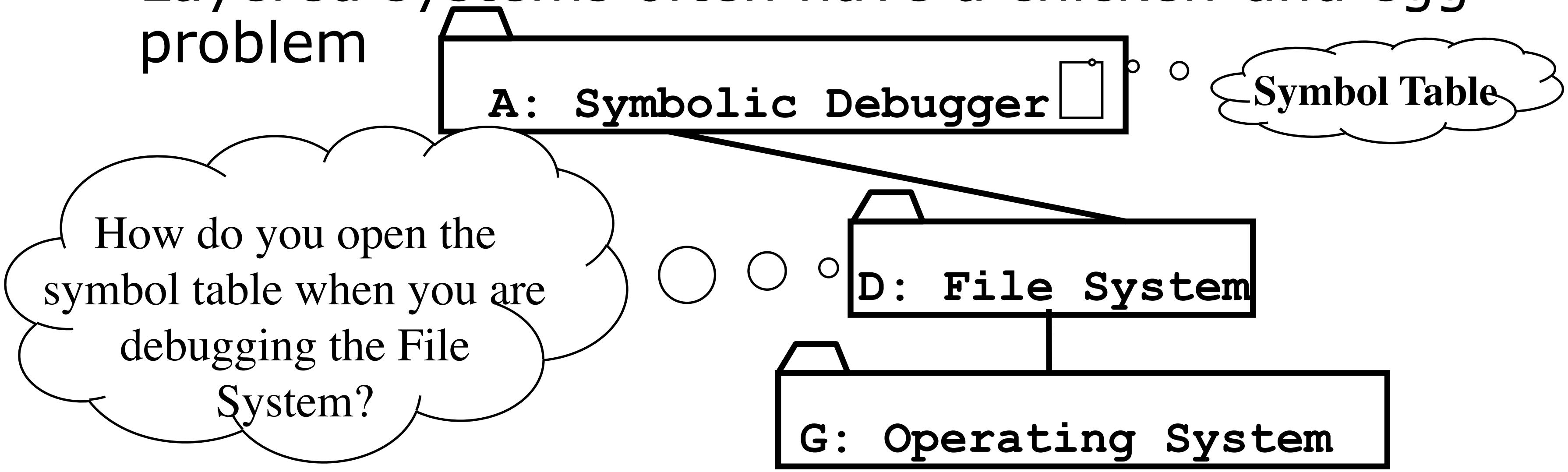
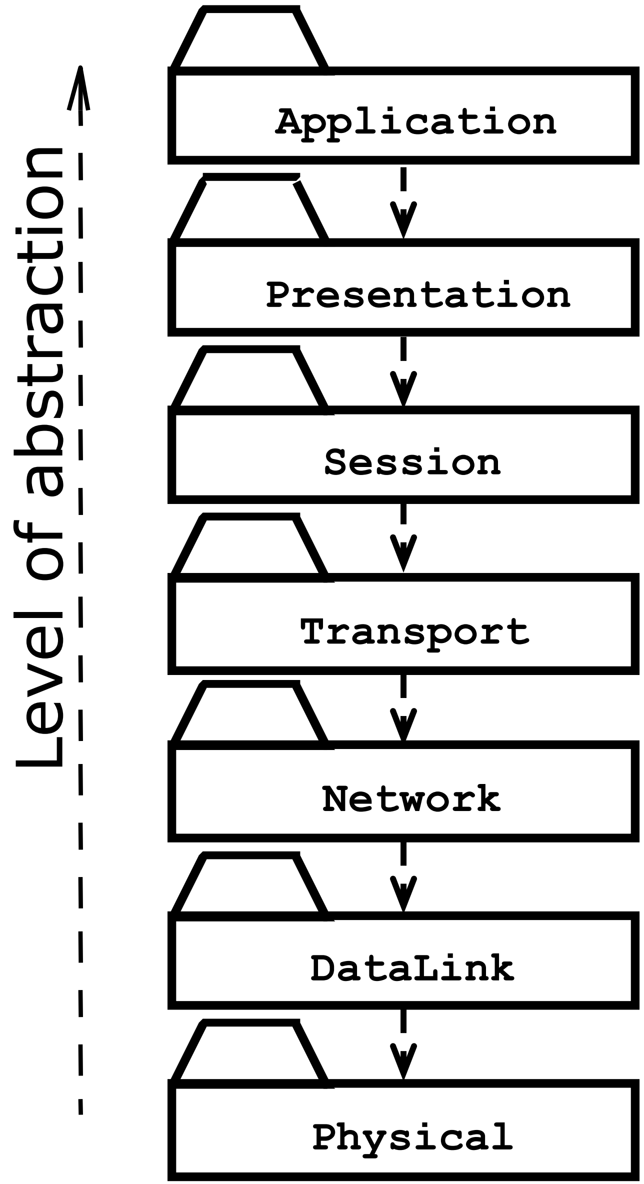
- Layered systems often have a chicken-and egg problem



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

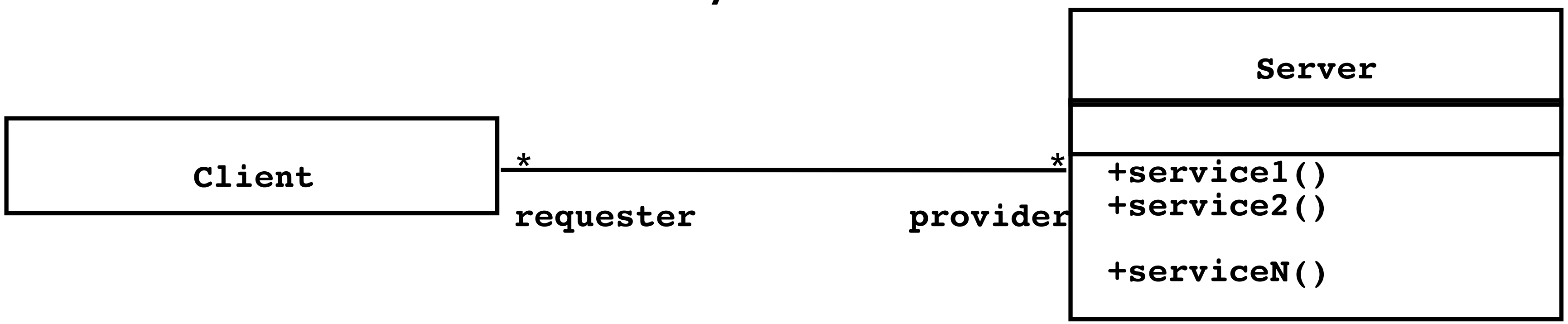
- ✓ Layered Architectural Style
  - ✓ Service-Oriented Architecture (SOA)
- Client/Server
- Peer-to-Peer
- Three-tier, Four-tier Architecture
- Repository
  - Blackboard
- Model-View-Controller
- Pipes and Filters

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.

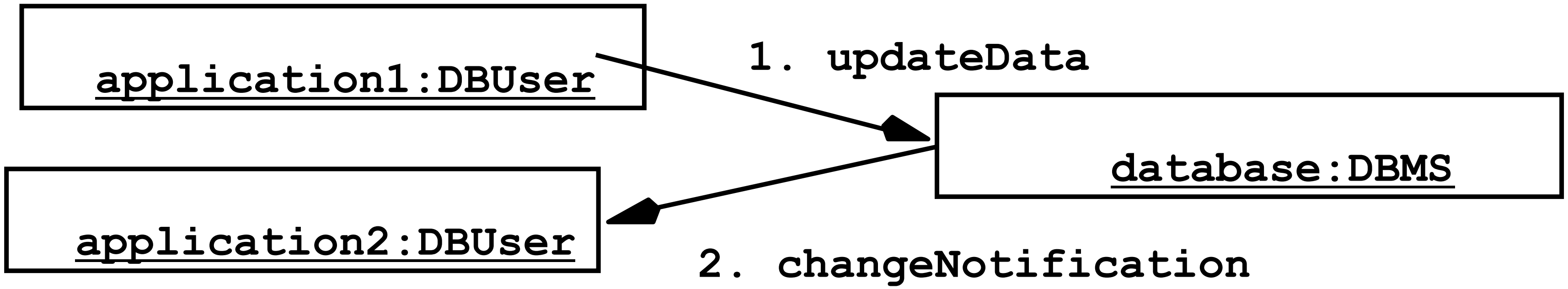


Design Goals for Client/Server Architectures

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	Server should be able to survive client and communication problems.

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

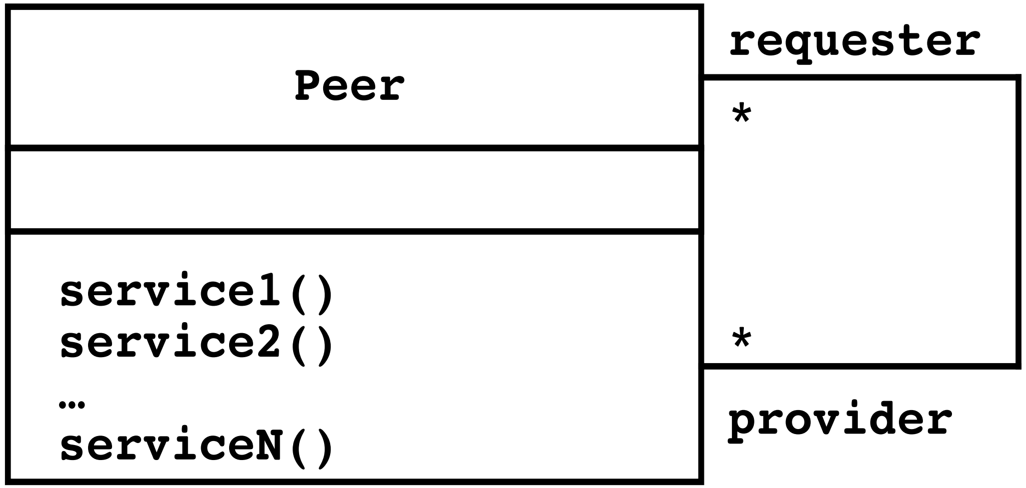
"Clients can be servers and servers can be clients"

Introduction a new abstraction: Peer

"Clients and servers can be both peers"

How do we model this statement? With Inheritance?

"A peer can be a client as well as a server".



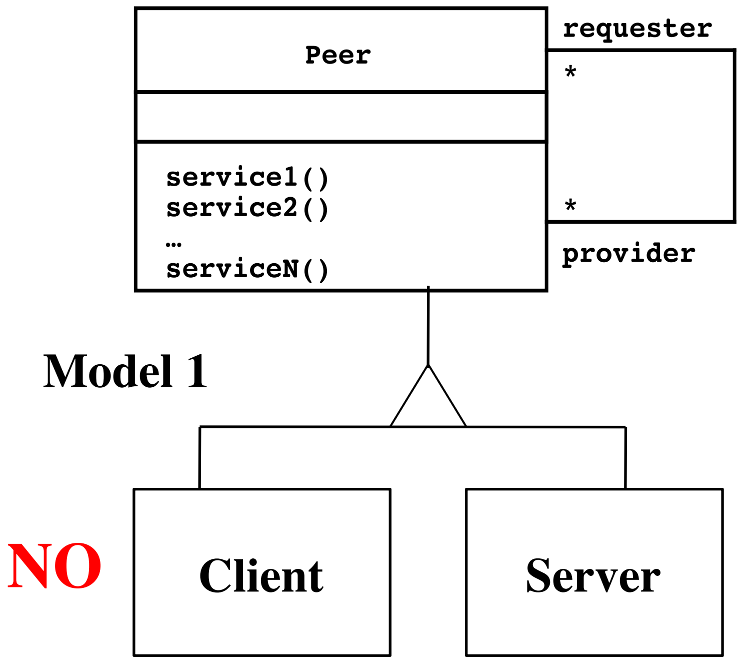
Relationship Client/Server & Peer-to-Peer

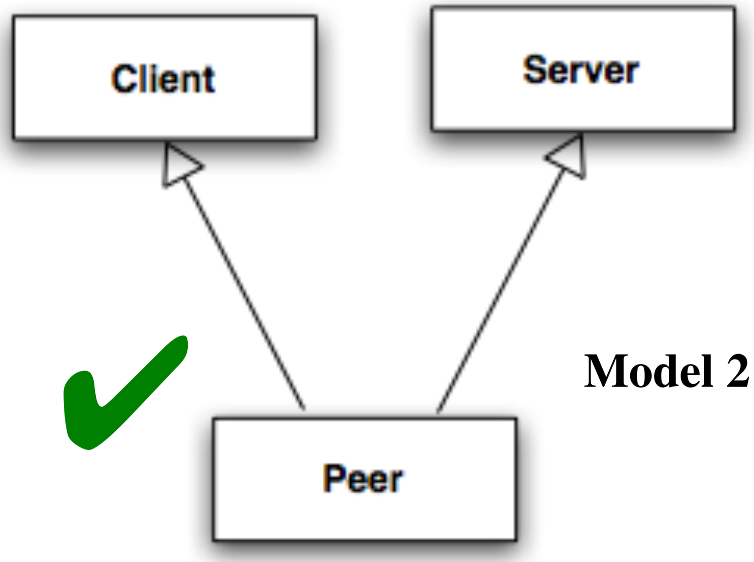
Problem statement "Clients can be servers and servers can be clients"

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

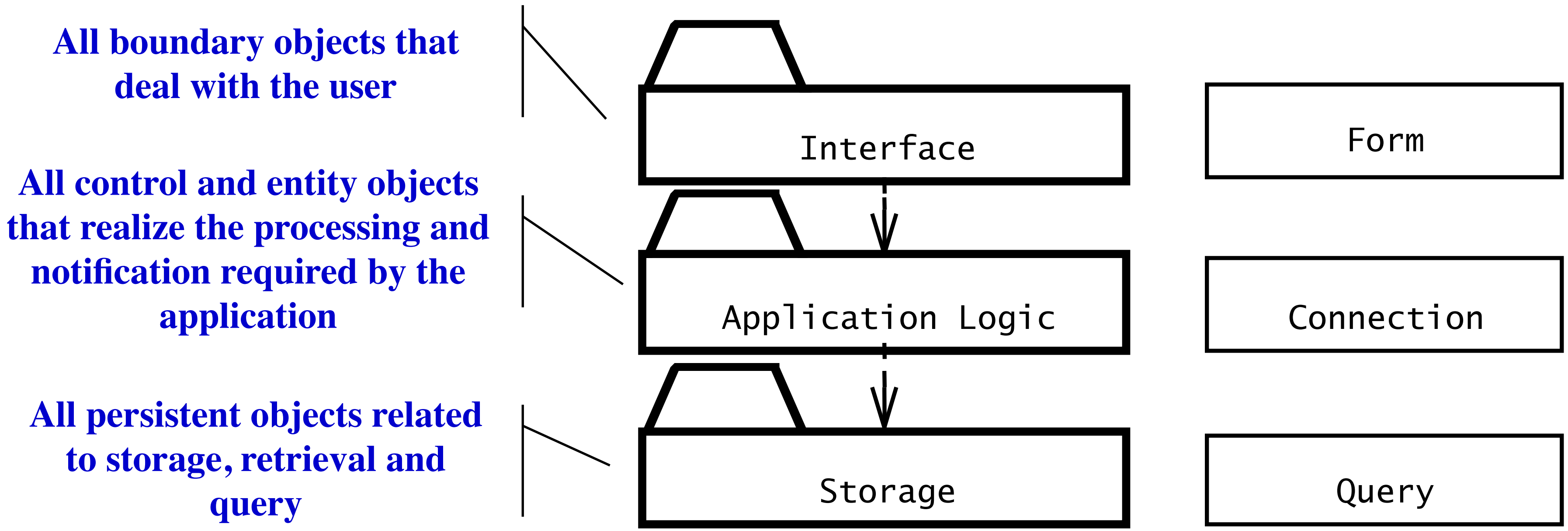
- Note: Layer is a type (e.g. class, subsystem) and Tier is an instance (e.g. object, hardware node)
- Layer and Tier are often used interchangeably.

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.

Three-tier architectural style.

- Subsystems are organized into three layers



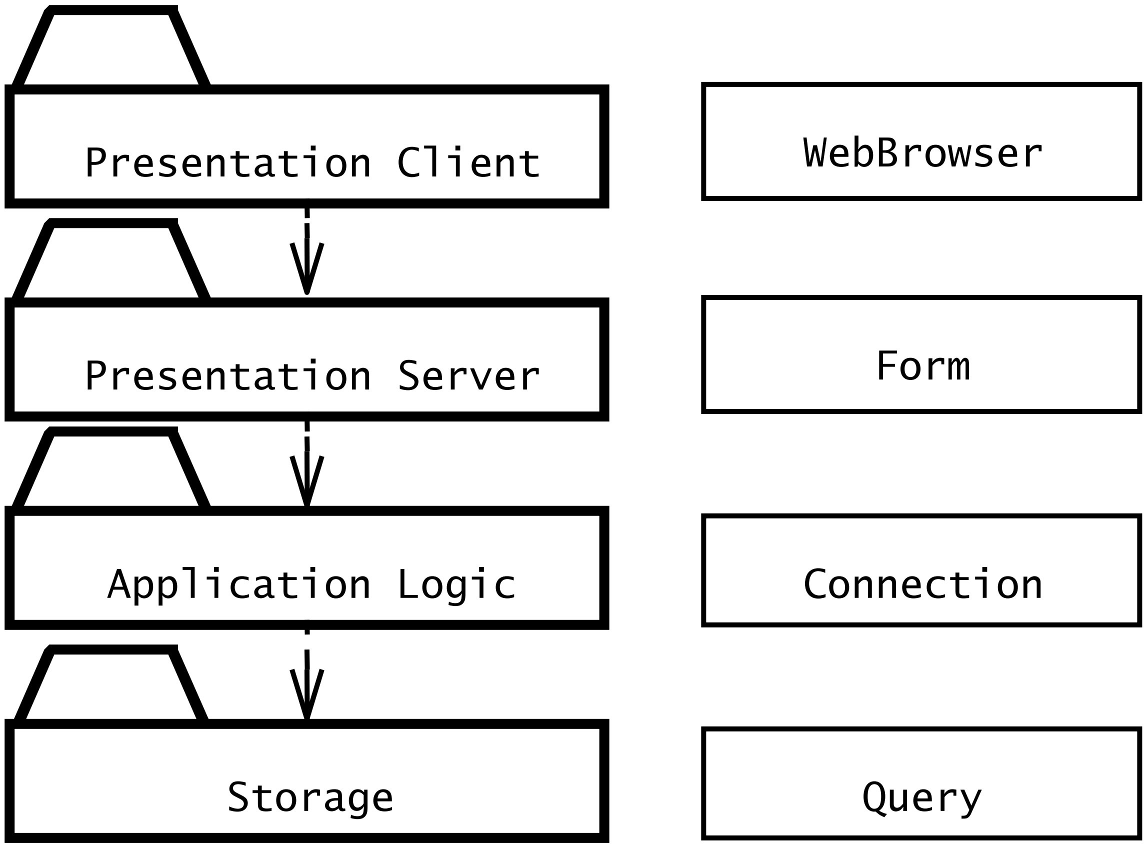
Example of a 4-Layered Architectural Style

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).

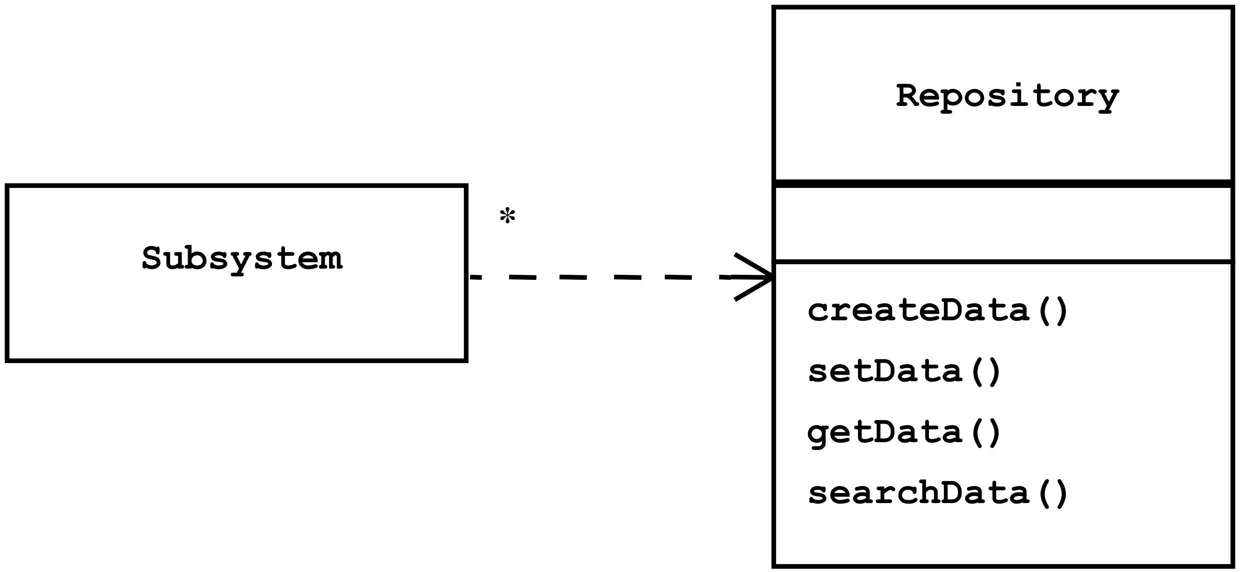
Four-tier architectural style.

- Subsystems are organized into four layers
- *Web-based applications*

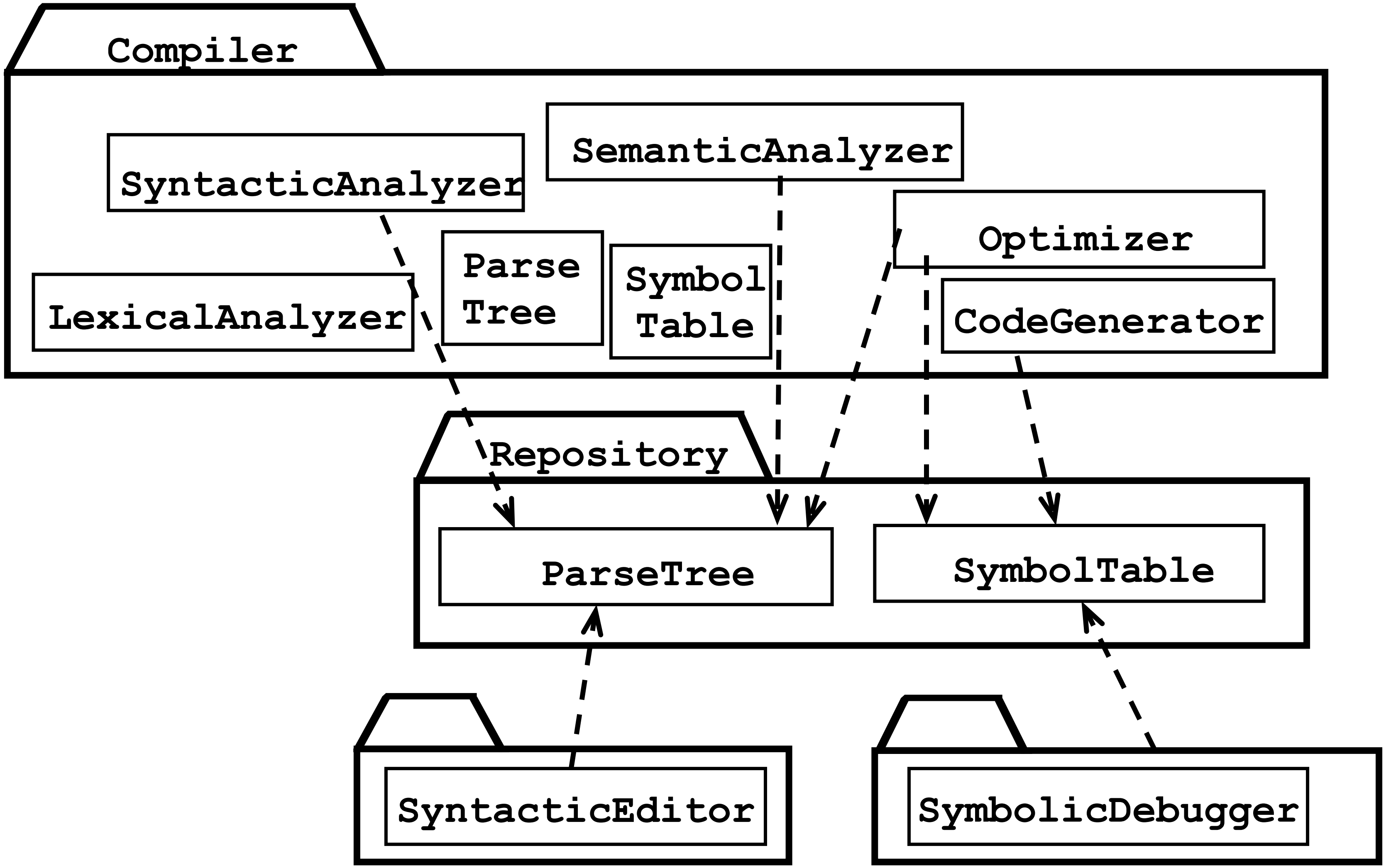


Repository Architectural Style

- 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**, <u>thus making it difficult to change the repository</u> 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) architectural 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

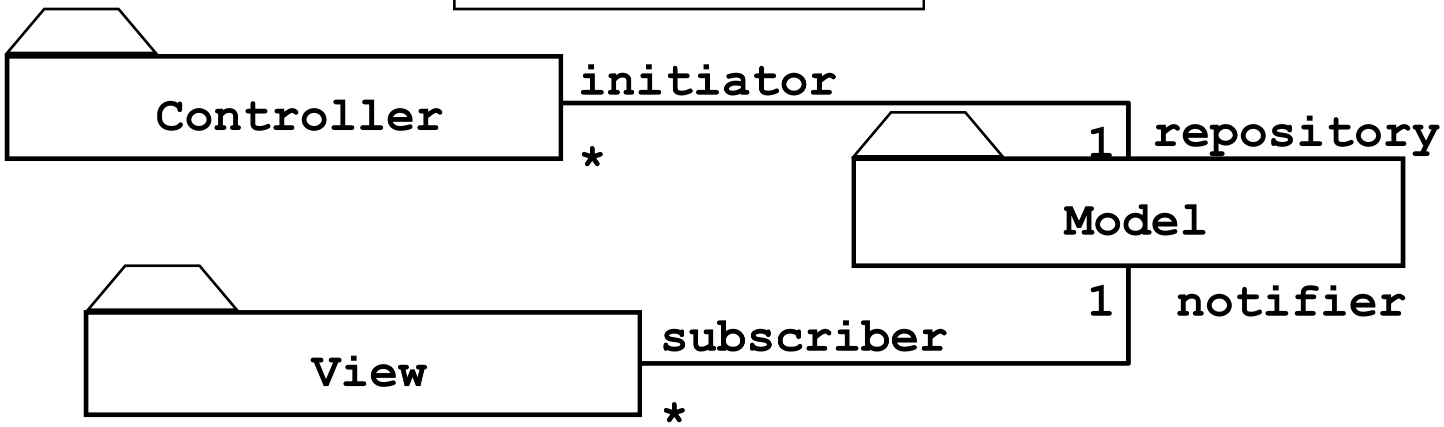
- Subsystems are classified into 3 different types

  Model subsystem: Responsible for application domain knowledge

  View subsystem: Responsible for displaying information to the user

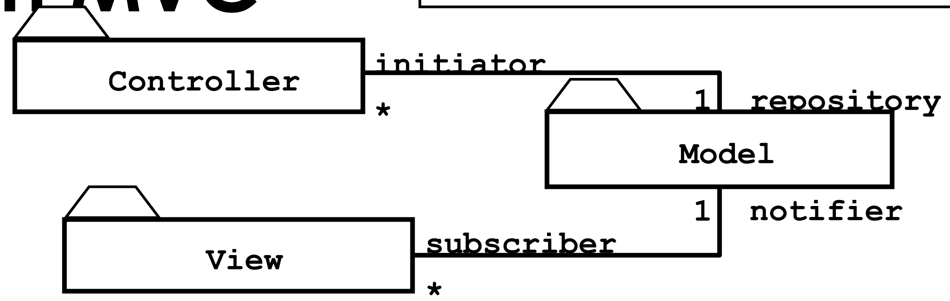
  Controller subsystem: Responsible for interacting with the user and notifying views of changes in the model

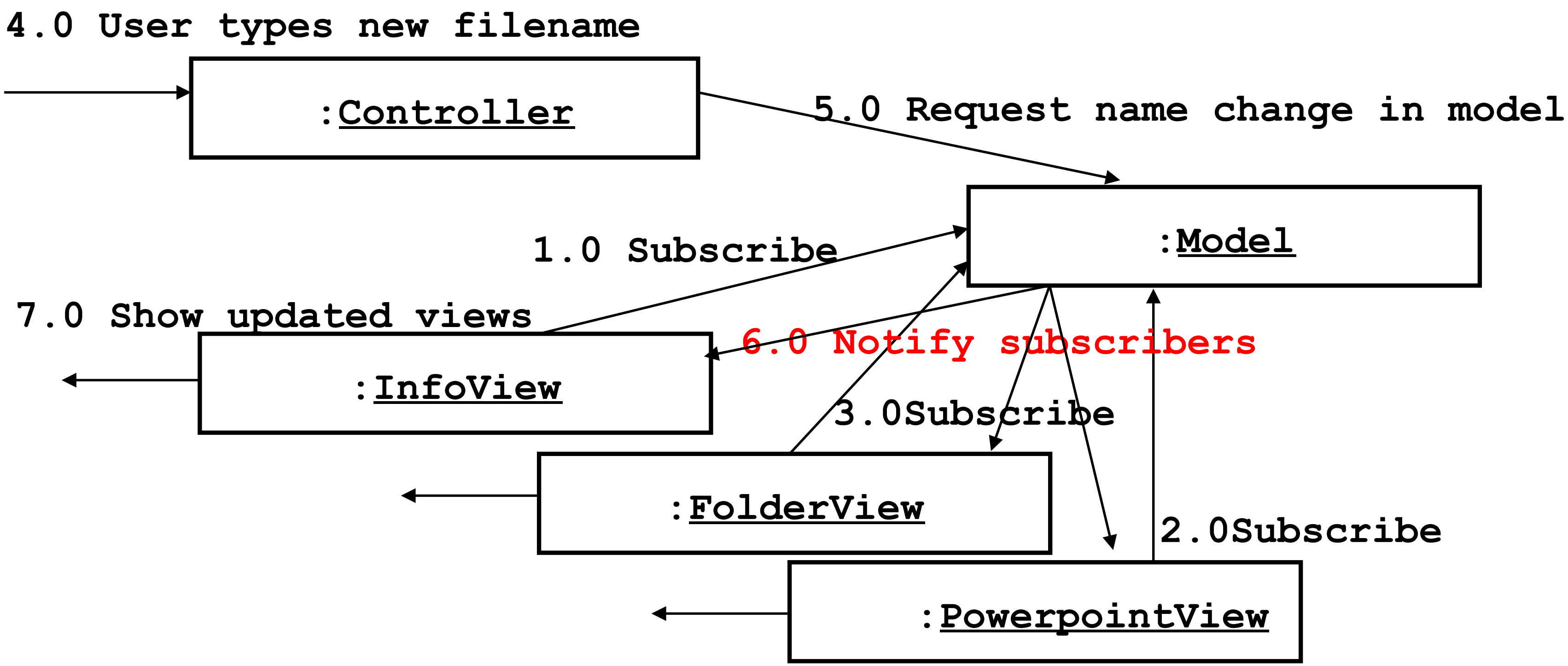
Class Diagram



Example: Modeling the Sequence of Events in MVC

UML Class Diagram





UML Communication Diagram

Review: UML Communication Diagram

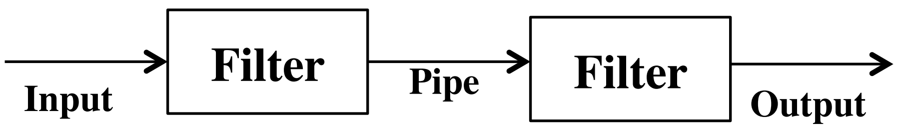
- A Communication Diagram visualizes the interactions between objects as a flow of messages. Messages can be events or calls to operations
- Communication diagrams describe the static structure as well as the dynamic behavior of a system:
  - The static structure is obtained from the UML class diagram
    - 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
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  - 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.