System Design

Design: HOW to implement a system

- **Goals:**
  - Satisfy the requirements
  - Satisfy the customer
  - Reduce development costs
  - Provide reliability
  - Support maintainability
  - Plan for future modifications
Design Issues

- Architecture
- User Interface
- Data Types
- Operations
- Data Representations
- Algorithms

System Design

- Choose high-level strategy for solving problem and building solution
- Decide how to organize the system into subsystems
- Identify concurrency / tasks
- Allocate subsystems to HW and SW components
Strategic vs. Local Design Decisions

- **Defn**: A high-level or *strategic* design decision is one that influences the form of (a large part) of the final code.

- Strategic decisions have the most impact on the final system.

- So they should be made carefully.

- **Question**: Can you think of an example of a strategic decision?

System Design

- **Defn**: The high-level strategy for solving an [information flow] problem and building a solution.
  - Includes decisions about organization of functionality.
  - Allocation of functions to hardware, software and people.
  - Other major conceptual or policy decisions that are prior to technical design.

- Assumes and builds upon thorough requirements and analysis.
Taxonomy of System-Design Decisions

- **Devise a system architecture**
- Choose a data management approach
- Choose an implementation of external control

System Architecture

- A collection of *subsystems* and interactions among subsystems.
- Should comprise a small number (<20) of subsystems.
- A subsystem is a package of classes, associations, operations, events and constraints that are interrelated and that have a reasonably well-defined interface with other subsystems.
- Example subsystems:
  - Database management systems (RDBMS)
  - Interface (GUI) package
Architectural Design Principles

- Decompose into subsystems *layers* and *partitions*.
- Separate application logic from user interface.
- Simplify the interfaces through which parts of the system will connect to other systems.
- In systems that use large databases:
  - Distinguish between *operational (transactional)* and *inquiry* systems.
  - Exploit features of DBMS.

Layered Subsystems

- Set of “virtual” worlds
- Each layer is defined in terms of the layer(s) below it
  - Knowledge is one-way: Layer knows about layer(s) below it
- Objects within layer can be independent
- Lower layer (server) supplies services for objects (clients) in upper layer(s)
**Example: Layered architecture**

<table>
<thead>
<tr>
<th>Interactive Graphics Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows Operations</td>
</tr>
<tr>
<td>Screen Operations</td>
</tr>
<tr>
<td>Pixel Operations</td>
</tr>
<tr>
<td>Device I/O Operations</td>
</tr>
</tbody>
</table>

**Closed Architectures**

- Each layer is built only in terms of the immediate lower layer
- Reduces dependencies between layers
- Facilitates change
Open Architectures

• Layer can use any lower layer
• Reduces the need to redefine operations at each level
• More efficient / compact code
• System is less robust / harder to change

Properties of Layered Architectures

• Top and bottom layers specified by the problem statement
  ▪ Top layer is the desired system
  ▪ Bottom layer is defined by available resources (e.g. HW, OS, libraries)

• Easier to port to other HW/SW platforms
Partitioned Architectures

- Divide system into weakly-coupled subsystems
- Each provides specific services
- Vertical decomposition of problem

Ex: Partitioned Architecture

Operating System

File System | Process Control | Virtual Memory Management | Device Control
Typical Application Architecture

<table>
<thead>
<tr>
<th>User dialogue control</th>
<th>Application package</th>
<th>Simulation package</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Window graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Screen graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pixel graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operating system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computer hardware</td>
<td></td>
</tr>
</tbody>
</table>

System Topology (also known as SW Architecture)

- Describe information flow
  - Can use DFD to model flow
- Some common topologies
  - Pipeline (batch)
  - Star topology
  - Peer-to-peer
Pipes-and-Filter

• The system has
  ▪ Streams of data (pipe) for input and output
  ▪ Transformation of the data (filter)

Ex: Pipeline Topology (Architecture)

Compiler:

source program

Lexical analyzer

Semantic analyzer

Code generator

Code optimizer

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Ex: Pipeline Topology (Architecture)

Compiler:

- Lexical analyzer
- Semantic analyzer
- Code generator
- Code optimizer

BNF grammar

source program

token stream

abstract syntax tree

code sequence

object code

Pipes and Filter

• Several important properties
  – The designer can understand the entire system’s effect on input and output as the composition of the filters
  – The filters can be reused easily on other systems
  – System evolution is simple
  – Allow concurrent execution of filters

• Drawbacks
  – Encourages batch processing
  – Not good for handling interactive application
  – Duplication in filters functions

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Ex: Star Topology (Architecture)

Monitoring system:
- Sensors
- Control panel
- SafeHome software
- Alarm
- Telephone line

- Sensor status
- Commands, data
- Display information
- On/Off signals, alarm type
- Number tones

Characteristics
- Scales up well
- Increased system capabilities
- Highly tolerant of failures

Examples: Napster and Skype

Peer-to-Peer (P2P)

- Each component acts as its own process and acts as both a client and a server to other peer components.
- Any component can initiate a request to any other peer component.

- Characteristics
  - Scales up well
  - Increased system capabilities
  - Highly tolerant of failures

- Examples: Napster and Skype
Client-Server

- Two types of components:
  - Server components offer services
  - Clients access them using a request/reply protocol
- Client may send the server an executable function, called a callback
  - The server subsequently calls under specific circumstances

Publish-Subscribe

- Components interact by broadcasting and reacting to events
  - Component expresses interest in an event by subscribing to it
  - When another component announces (publishes) that event has taken place, subscribing components are notified
  - Implicit invocation is a common form of publish-subscribe architecture
    - Registering: subscribing component associates one of its procedures with each event of interest (called the procedure)
  - Examples: RSS, Social Media; implement via Observer Design Pattern

- Characteristics
  - Strong support for evolution and customization
  - Easy to reuse components in other event-driven systems
  - Need shared repository for components to share persistent data
  - Difficult to test
Repositories

- Two components
  - A central data store
  - A collection of components that operate on it to store, retrieve, and update information
  - Example: EMR (?), Personnel Database, Student Records

- The challenge is deciding how the components will interact
  - A traditional database: transactions trigger process execution
  - A blackboard: the central store controls the triggering process
  - Knowledge sources: information about the current state of the system’s execution that triggers the execution of individual data accessors

Repositories (continued)

- Major advantage: openness
  - Data representation is made available to various programmers (vendors) so they can build tools to access the repository
  - But also a disadvantage: the data format must be acceptable to all components
Combining Architectural Styles

- Actual software architectures rarely based on purely one style

- Architectural styles can be combined in several ways
  - Use different styles at different layers (e.g., overall client-server architecture with server component decomposed into layers)
  - Use mixture of styles to model different components or types of interaction (e.g., client components interact with one another using publish-subscribe communications)

- If architecture is expressed as collection of models, documentation must be created to show relation between models
Taxonomy of System-Design Decisions

- Devise a system architecture
- **Choose a data management approach**
- Choose an implementation of external control
Choosing a Data Management Approach

- **Databases:**
  - **Advantages:**
    - Efficient management
    - Multi-user support.
    - Roll-back support
  - **Disadvantages:**
    - Performance overhead
    - Awkward (or more complex) programming interface
    - Hard to fix corruption

Choosing a Data Management Approach (continued)

- **“Flat” files**
  - **Advantages:**
    - Easy and efficient to construct and use
    - More readily repairable
  - **Disadvantages:**
    - No rollback
    - No direct complex structure support
    - Complex structure requires a grammar for file format
Flat File Storage and Retrieval

- Useful to define two components (or classes)
  - **Reader** reads file and instantiates internal object structure
  - **Writer** traverses internal data structure and writes out presentation

- Both can (should) use formal grammar
  - Tools support: Yacc, Lex.

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Taxonomy of System-Design Decisions

- Devise a system architecture
- Choose a data management approach
- **Choose an implementation of external control**
Implementation of External Control

Four general styles for implementing software control

- **Procedure-driven:**
  - Control = location in the source code.
  - Requests block until request returns
  - Example: standard computational and/or scientific applications

- **Event-Driven: Control resides in dispatcher**
  - Uses callback functions registered for events
  - Dispatcher services events by invoking callbacks
  - Example: graphical user interfaces; windowing systems

Implementation of External Control

- **Concurrent**
  - Control resides in multiple, concurrent objects
  - Objects communicate by passing messages
    - across busses, networks, or memory.
  - Example: onboard electronics in vehicles

- **Transactional**
  - Control resides in servers and saved state
  - Example: Many server-side E-systems are like this
Sample Concurrent System

Dispatcher Model
(event driven)

Events
Get event,
call a
procedure

Process event type 1

Process event type 2

Process event type N

Window manager & Notifier
Application code

Control

Radar

Car

x1: integer
x2: integer
tinc: integer
vc: integer
x1: integer
vc: integer
tinc: integer
x1: integer
tinc: integer
x1: integer
tinc: integer

v: integer
vc: integer
vt: integer
v: integer
vc: integer
vt: integer
v: integer
vc: integer
vt: integer

setv: integer
realv: integer

car speed
throttle control
target acquisition
target loss
distance
car speed

Set event and
real value

Process event type 1

Process event type 2

Process event type N

Get event,
call a
procedure

Window manager & Notifier
Application code

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Event-driven architecture in UI toolkits

- **Window manager**
- **User-interface component**
- **Application code**

Get events and dispatch

Events

- Widget1 (e.g. Button)
- Widget2 (e.g. TextBox)
- Widget3 (e.g. Dialog)

- Button Listener
- Text Listener
- Listener

**Typical Dispatcher Code**

```
while (!quit) {
    WaitEvent(timeout, id);
    switch (id) {
        case ID1: Procedure1(); break;
        case ID2: Procedure2(); break;
        ....
    }
}
```

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Transactional Model

- **ACID Model:**
  - **Atomicity:** all or nothing with respect to permanent effect of actions
  - **Consistency:**
    - at start of actions, system is in consistent state;
    - upon completion (i.e. ‘commit’), system is consistent?
  - **Isolation:** All transactions work as if in isolation
  - **Durability:** Entities stored in persistent media (e.g., database, file)

- **2-step Commit Protocol:**
  - First step initiates the actions (if abort executed, rollback to previous consistent state)
  - Second step: commit the effect of the actions.

- **Examples:**
  - Relational databases
  - Graphical/word processing editors (think about “undo” operation)

Reference: [http://www.agiledata.org/essays/transactionControl.html](http://www.agiledata.org/essays/transactionControl.html)
# General Design Concerns

- Modularity
- Abstraction
- Cohesion
- Coupling
- Information Hiding
- Abstract Data Types
- Identifying Concurrency
- Global Resources
- Boundary Conditions
- Tradeoffs

## Modularity

- Organize modules according to resources/objects/data types
- Provide cleanly defined interfaces
  - operations, methods, procedures, ...
- Hide implementation details
- Simplify program understanding
- Simplify program maintenance
Abstraction

- Control abstraction
  - structured control statements
  - exception handling
  - concurrency constructs

- Procedural abstraction
  - procedures and functions

- Data abstraction
  - user defined types

Abstraction (cont.)

- Abstract data types
  - encapsulation of data

- Abstract objects
  - subtyping
  - generalization/inheritance
Cohesion

• Contents of a module should be *cohesive*
  ▪ Somehow related

• Improves maintainability
  ▪ Easier to understand
  ▪ Reduces complexity of design
  ▪ Supports reuse

(Weak) Types of cohesiveness

• Coincidentally cohesive
  ▪ contiguous lines of code not exceeding a maximum size

• Logically cohesive
  ▪ all output routines

• Temporally cohesive
  ▪ all initialization routines
(Better) Types of cohesiveness

- Procedurally cohesive
  - routines called in sequence
- Communicationally cohesive
  - work on same chunk of data
- Functionally cohesive
  - work on same data abstraction at a consistent level of abstraction

Example: Poor Cohesion

```vbc
package Output is
    procedure DisplayDice(. . .);
    procedure DisplayBoard(. . .);`
Example: Good Cohesion

package Dice is
  procedure Display ( . . .);
  procedure Roll( . . .);

Coupling

- **Connections** between modules
- **Bad coupling**
  - Global variables
  - Flag parameters
  - Direct manipulation of data structures by multiple classes
Coupling (cont.)

- **Good coupling**
  - Procedure calls
  - Short argument lists
  - Objects as parameters

- Good coupling improves maintainability
  - Easier to localize errors, modify implementations of an objects, ...

Information Hiding

- Hide decisions likely to change
  - Data representations, algorithmic details, system dependencies

- Black box
  - Input is known
  - Output is predictable
  - Mechanism is unknown

- Improves maintainability
Information Hiding

Abstract data types

- Modules (Classes, packages)
  - Encapsulate data structures and their operations
  - Good cohesion
    - implement a single abstraction
  - Good coupling
    - pass abstract objects as parameters
  - Black boxes
    - hide data representations and algorithms
Identifying Concurrency

- **Inherent concurrency**
  - May involve synchronization
  - Multiple objects receive events at the same time without interacting
  - Example:
    - User may issue commands through control panel at the same time that the sensor is sending status information to the SafeHome system

Determining Concurrent Tasks

- **Thread of control**
  - Path through state diagram with only one active object at any time

- Threads of control are implemented as **tasks**
  - Interdependent objects
  - Examine state diagram to identify objects that can be implemented in a task
Global Resources

- Identify global resources and determine access patterns

- Examples
  - physical units (processors, tape drives)
  - available space (disk, screen, buttons)
  - logical names (object IDs, filenames)
  - access to shared data (database, file)

Boundary Conditions

- Initialization
  - Constants, parameters, global variables, tasks, guardians, class hierarchy

- Termination
  - Release external resources, notify other tasks

- Failure
  - Clean up and log failure info
Identify Trade-off Priorities

- Establish priorities for choosing between incompatible goals
- Implement minimal functionality initially and embellish as appropriate
- Isolate decision points for later evaluation
- Trade efficiency for simplicity, reliability, . . .