Advanced Topics of Software Engineering (ASE)

Chapter 2. From requirements to system design

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From requirements to system design

Formal definition of the structure of a system (1)

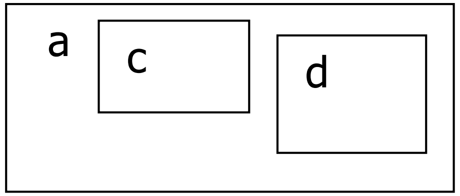
- Let us first formally define the structure of **system S**
  - by the tuple $S \coloneqq (C, I, CON)$
  - with C denoting the **components**
  - with $env \in C$ denoting the system **environment**
  - with I denoting the **interfaces** of the components
  - and $CON \subseteq I \times I$ denoting the **connection between interfaces**.

- A component can be a system itself
  - this establishes a hierarchy of components
  - Example see next slide

Formal definition of the structure of a system (2)

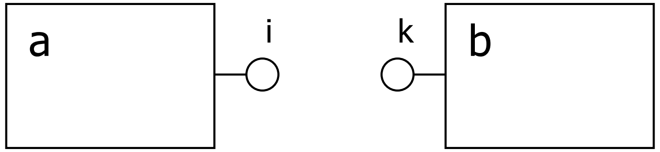
- Parent relationship between components (total function)
  - Example
    - parent(c) = parent(d) = a
    - parent(a) = *env*

$$\boldsymbol{parent}: C \rightarrow C$$



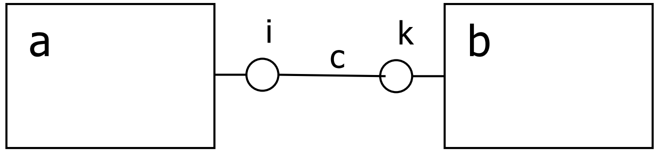
- Interface-component relationship (total function)
  - Example
    - assigned(i) = a
    - assigned(k) = b

$$\boldsymbol{assigned}: I \rightarrow C$$

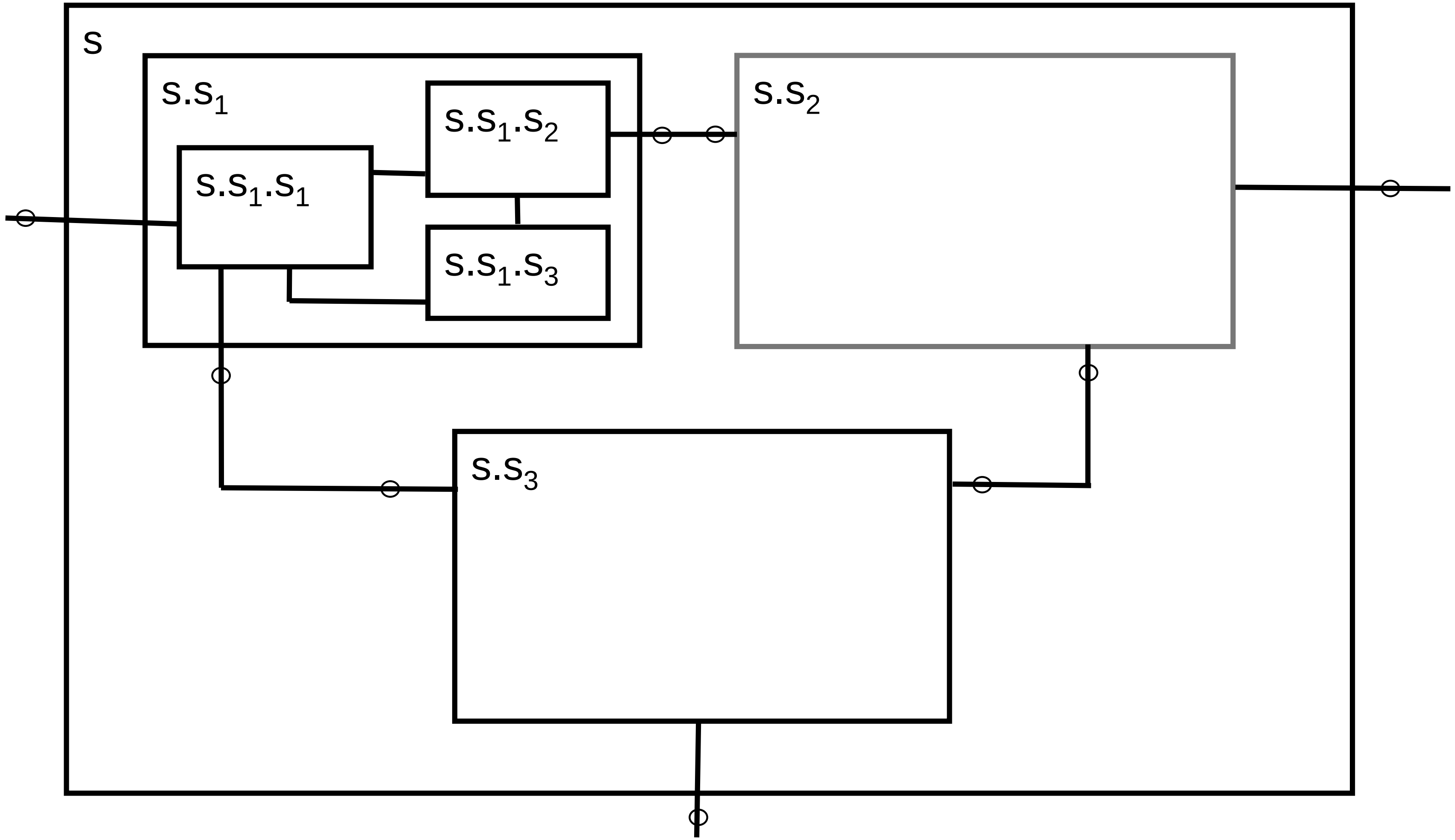


- Connection (CON) between interfaces (total function)
  - Example
    - connected(c)=(i,k)

$$\boldsymbol{connected}: CON \rightarrow (I \times I)$$



Hierarchical structure of a system



Quantitatively measuring coupling

- For the sake of simplicity let us consider coupling of a system as the *normalized number of connections between components at the same hierarchical level ("not so bad", factor* α*) and the normalized number of connections at different hierarchical levels ("a bit worse", factor 1-* α*).*

$$coupling: S \rightarrow \mathbb{R}$$

$$coupling(s) := \alpha * \frac{\left|\left\{con \in s.CON \,\middle|\, \exists i,j \in s.I: con = connected(i,j) \wedge parent\left(assigned(i)\right) = parent\left(assigned(j)\right)\right\}\right|}{|s.C|}$$

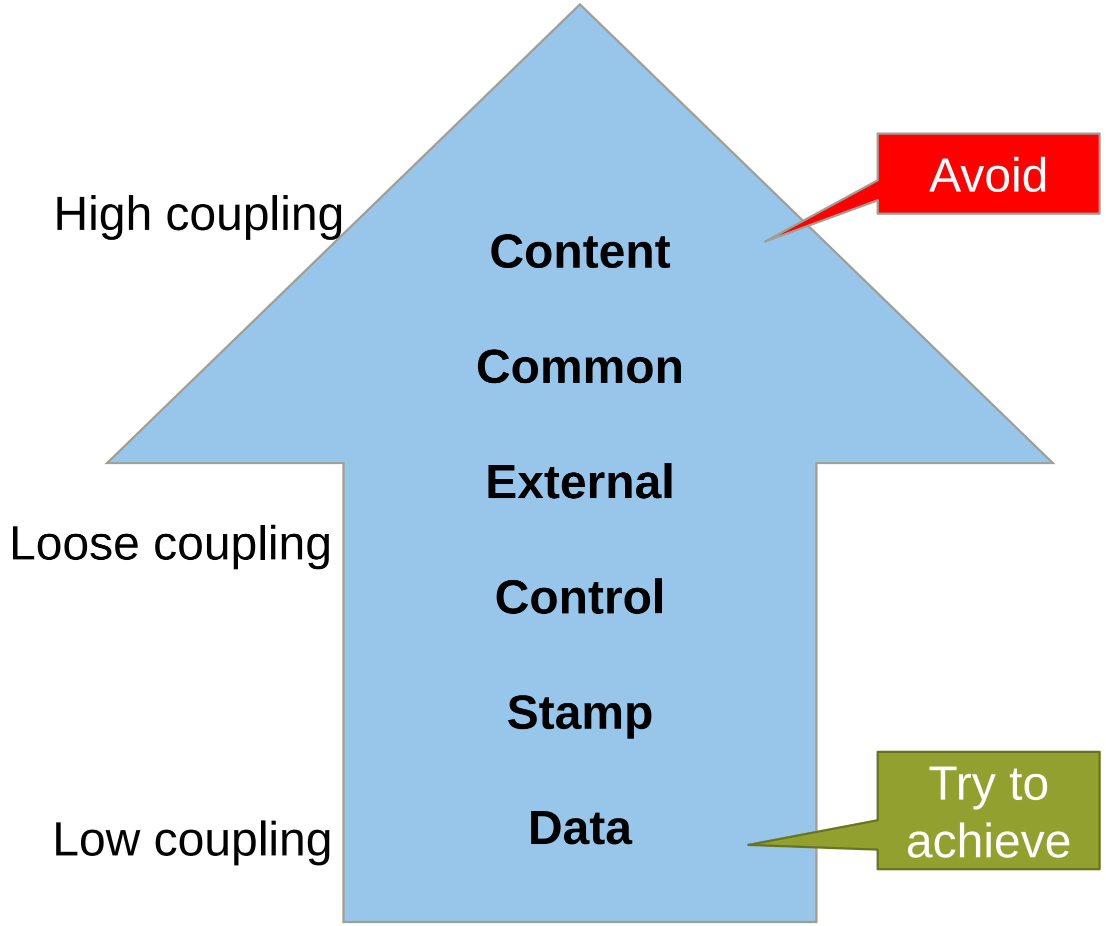
$$+ (1-\alpha) * \frac{\left|\left\{con \in s.CON \,\middle|\, \exists i,j \in s.I: con = connected(i,j) \wedge parent\left(assigned(i)\right) \neq parent\left(assigned(j)\right)\right\}\right|}{|s.C|}$$

- Note: One could put more emphasis on the top-level components than on the lower-level components.

- The coupling of a system s_1 is smaller than that of s_2
  - iff $coupling(s_1) < coupling(s_2)$

For a different treatment and more details, see ["A unified framework for coupling measurement in object-oriented systems." Briand, L. C., Daly, J. W., and Wüst, J. K. (1999)]

Types of coupling in software



[Content, Common, etc. are interaction patterns, described next]

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Content coupling

- One component directly affects the working of another component.
- Content coupling occurs when a component changes another component's data or when control is passed from one component to the middle of another
  - (as in a jump).

- Example - component A handles 'customer lookup'
  - When a customer record is not found, component A adds the customer by directly modifying the content of the data structure containing customer information (which is the responsibility of component B - 'creating customers’).

Almost any change to component B requires changes to component A.

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Common coupling

- Two components have shared data.

- The name originates from the use of COMMON blocks in FORTRAN.

- Its equivalent in block-structured languages is the use of global variables.

- Lack of clear responsibility for the data
- Reduces readability
- Difficult to determine all the components that affect a data element (reduces maintainability)
- Difficult to reuse components
- Reduces ability to control data accesses

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

External coupling

- Components communicate through an external medium such as a:
  - File
  - Device interface
  - Protocol
  - Data format

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Control coupling

- One component directs the execution of another component by passing the necessary control information.
  - This is usually accomplished by means of flags that are set by one component and reacted upon by the dependent component.

- May be either *good or bad*, depending on the situation.
  - *Good* if parameters allow factoring and reuse of functionality.
  - Example - sort that takes a comparison function as an argument.
    - The sort function is clearly defined: return a list in sorted order, where sorted is determined by a parameter.

  - *Bad* if parameters indicate completely different behavior or
  - if components are not independent
    - Component B must know the internal structure of component A – might affect reusability

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Stamp coupling

- Complete data structures are passed from one component to another.
- With stamp coupling, the precise format of the data structures is a common property of those components

- Example
  - calculateSalary(Employee employee)

The second component has more information than it needs

Define interfaces to limit access from clients

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Data coupling

- Component passes data (not data structures) to another component
- Good, if it can be achieved
- Example
  - calculateSalary(String name, int noOfHours, int salPerHour)

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Cohesion

- How closely related are the different responsibilities of a component
- The degree of interaction within a component
- Make cohesion as strong as possible

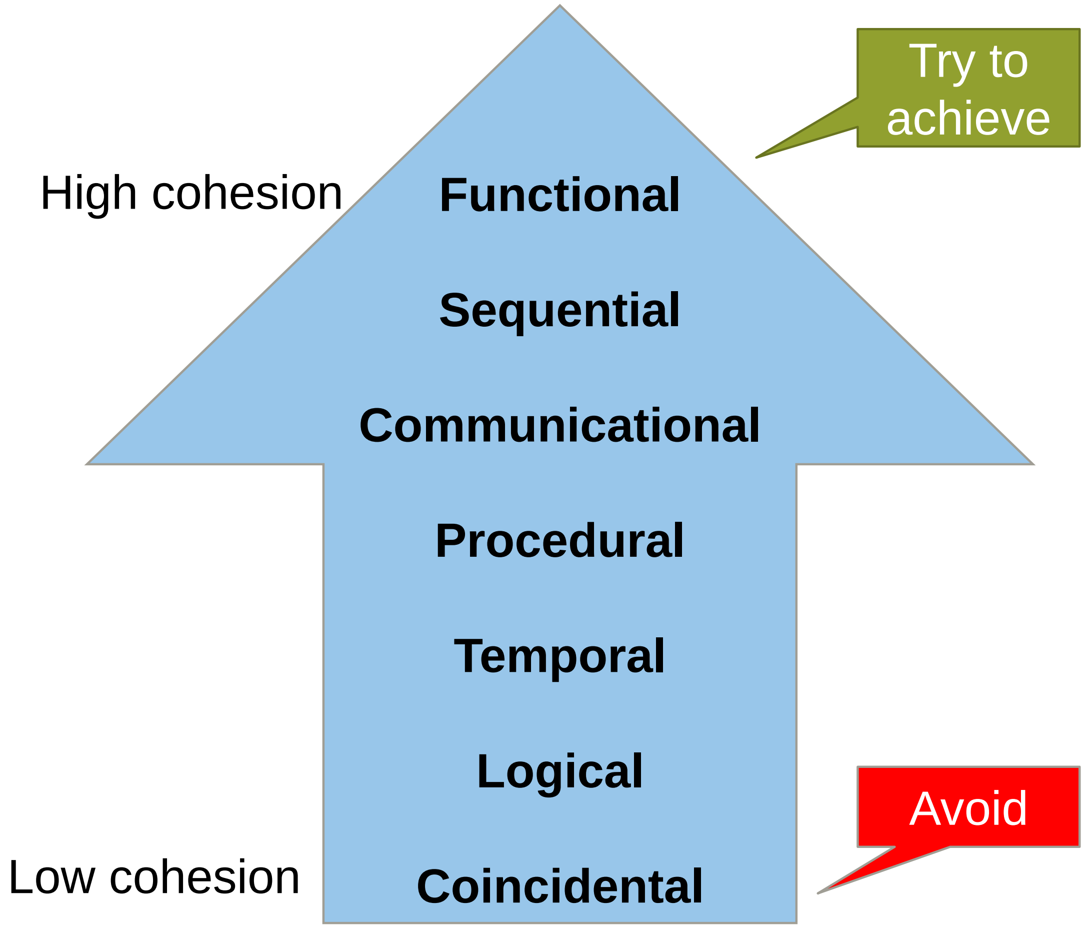
Coupling and cohesion are highly interrelated

A component's cohesion characterizes its internal interdependencies.

Strive for low coupling and high cohesion

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Types of cohesion



["Structured Design" Yourdon, E. and Constantine, L. L. (1975)]

Coincidental cohesion

- Elements are grouped into components in a haphazard way.
- There is no significant relation between the elements.
- Parts of the component are unrelated (unrelated functions, processes, or data)
- Accidental
- Worst form

- Example – a component that
  - Prints next line
  - Reverses string of characters in 2nd argument
  - Adds 7 to 3rd argument
  - Converts 4th argument to float

Degrades maintainability and components are not reusable

Break into separate modules each performing one task

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Logical cohesion

- Elements of component are related logically and not functionally.
- Several logically related elements are in the same component and one of the elements is selected by the client component.

- Example:
  - A component reads inputs from tape, disk, and network.
  - All the code for these functions are in the same component.
  - Operations are related, but the functions are significantly different.

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Temporal cohesion

- The elements are independent, but they are activated at about the same point in time.

- Initialization component example
  - open old db, new db, transaction db, print db
  - initialize sales district table
  - read first transaction record
  - read first old db record

- Actions weakly related to one another, but strongly related to actions in other modules
- Code spread out --- not maintainable or reusable

For the above example, define these initializers in the proper modules and then have an initialization module call each operation.

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Procedural cohesion

- Elements of a component are related only to ensure a particular order of execution.

- Example
  - Write output record
  - Read new input record
  - Pad input with spaces
  - Return new record

Actions are still weakly connected and unlikely to be reusable.

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Communicational cohesion

- The elements of a component operate on the same (external) data.

- Example:
  - Update the record in a database
  - Print the record

Still leads to less reusability --- break it up

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Sequential cohesion

- The output of one part is the input to another.
- Data flows between parts (different from procedural cohesion).
- Occurs naturally in functional programming languages.
- Good situation

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Functional cohesion

- Every essential element to a single computation is contained in the component
- Such a component often transforms a single input into a single output
- Ideal situation

- Increases
  - Reusability
  - Testability
  - Understandability
  - Learnability
- Corrective maintenance is easier
  - Fault isolation
  - Reduced regression faults
- Easier to extend product (extensibility)

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

Conclusion

Strive for low coupling and high cohesion

- Communication between programmers becomes simpler.
  - Decisions can be made locally and without interfering with other components.
- Correctness proofs become easier to derive.
- It is less likely that changes will propagate to other components.
  - Avoids ripple-effects (low coupling)
  - Allows changes to be local (high cohesion)
  - Reduces maintenance costs
- Increases reusability
- The comprehensibility of components is increased.
  - Manifests in small set of component interfaces
  - Simple component interfaces allow for an understanding of a component independent of the context in which it is used
- Less error-prone
- But … don’t overdo it!

["Software Engineering: Principles and Practice." Van Vliet H. (2008)]

From requirements to system design

[… tbc]

Single responsibility principle

"There should never be more than one reason for a class to change."

["Agile Software Development, Principles, Patterns, and Practices." Martin, R. C.]

- A class should only have one reason to change.

- If there are two reasons for a class to change, we have to split the functionality into two classes.
  - Each class will handle only one responsibility.
  - If we need to make a change, we should make it in the class that handles it.

- This leads to cohesion at the package/implementation level.

- The single responsibility principle is a simple and intuitive principle, but in practice it is sometimes hard to get it right!

Responsibility

"… a responsibility is a family of functions that serves one particular actor."

["Agile Software Development, Principles, Patterns, and Practices." Martin, R. C.]

- Core functionality of a class (what a class does)
- The more a class does, the more likely it will change.
- The more a class changes, the more likely it will affect its associated classes.

Single responsibility principle

["SOLID development principles." Bailey D. (2009)]

From requirements to system design

2.1. Software architecture

- 2.1.1. Software modules and software components
- 2.1.2. Dependency structure matrix
- 2.1.3. Guidelines for modular design
  - 2.1.3.1. Low coupling and high cohesion
  - 2.1.3.2. Single responsibility principle
  - **2.1.3.3. Separation of concerns**
  - 2.1.3.4. Liskov’s substitution principle
  - 2.1.3.5. Interface-segregation principle
  - 2.1.3.6. Anticipate change
  - 2.1.3.7. Don't repeat yourself
- 2.1.4 Architecture and external quality

2.2. Antipatterns

[… tbc]

Separation of concerns

- Talk about different things ("features") in different places
  - Functional and non-functional
  - Example: business logic, presentation, data layer

- In functional context, related to the principle of low coupling and high (functional) cohesion.

- Addresses limitations of human cognition.

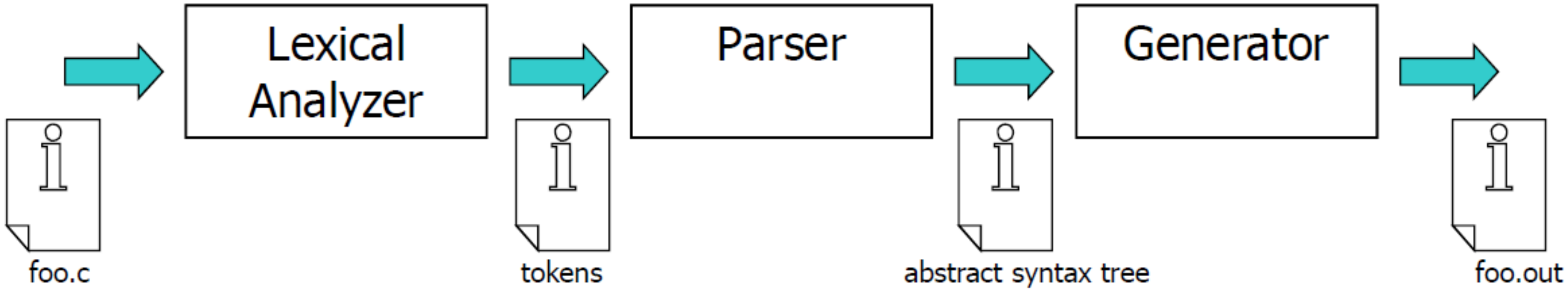
- Humans are only able to process ~7 data units at a time.

- Thus, functionality should not be overly scattered.

- Minimize responsibilities-per-component ratio.

- Components should only encapsulate semantically related functionalities.

Separation of concerns



- Each component fulfills its own distinct purpose.
- Functionalities are encapsulated within components.
- Components can be replaced arbitrarily.

Open/closed principle

Software entities (classes, modules and functions) should be open for extension, but closed for modifications.

["Object-Oriented Software Construction." Bertrand Meyer (1988)]

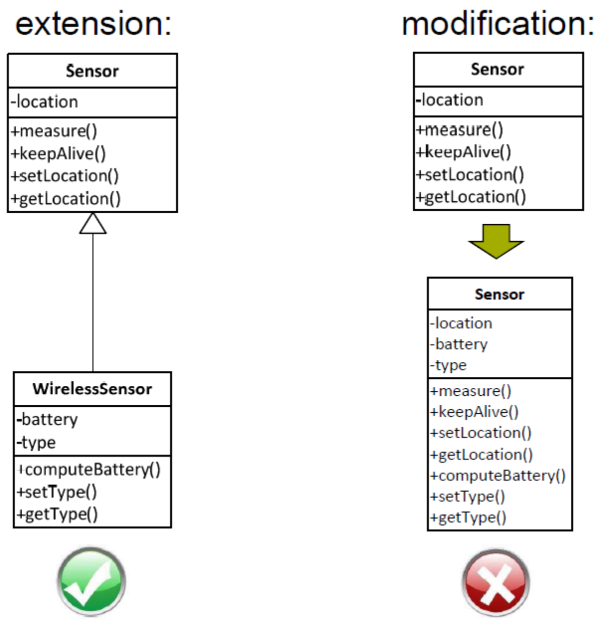
- A module will be said to be ***open*** if it is still available for extension.
  - For example, it should be possible to add fields to the data structures it contains, or new elements to the set of functions it performs.

- A module will be said to be ***closed*** if it is available for use by other modules.
  - This assumes that the module has been given a well-defined, stable description (the interface in the sense of information hiding).

["Agile Software Development, Principles, Patterns, and Practices." Martin R. C. (2002)]

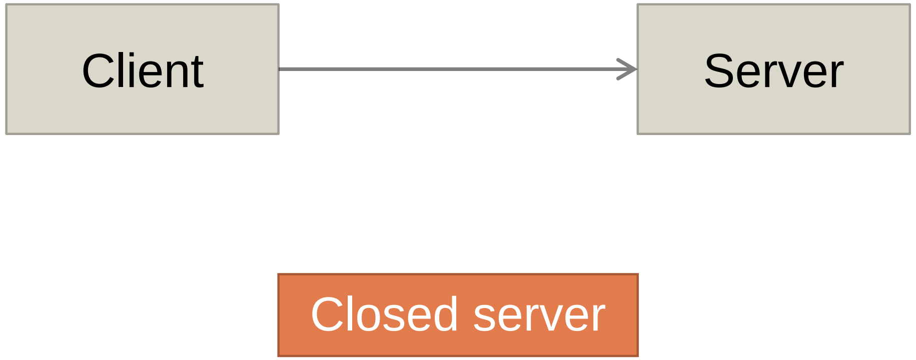
Conforming to the open/closed principle

- Open for extension
  - Behavior of the module can be extended
  - We are able to change what the module does
- Closed for modification
  - Extending behavior does not result in changes to the source, binary, or code of the module
  - Avoids unanticipated effects on dependent components
- Highly related to the inheritance and polymorphism paradigm of object-oriented programming



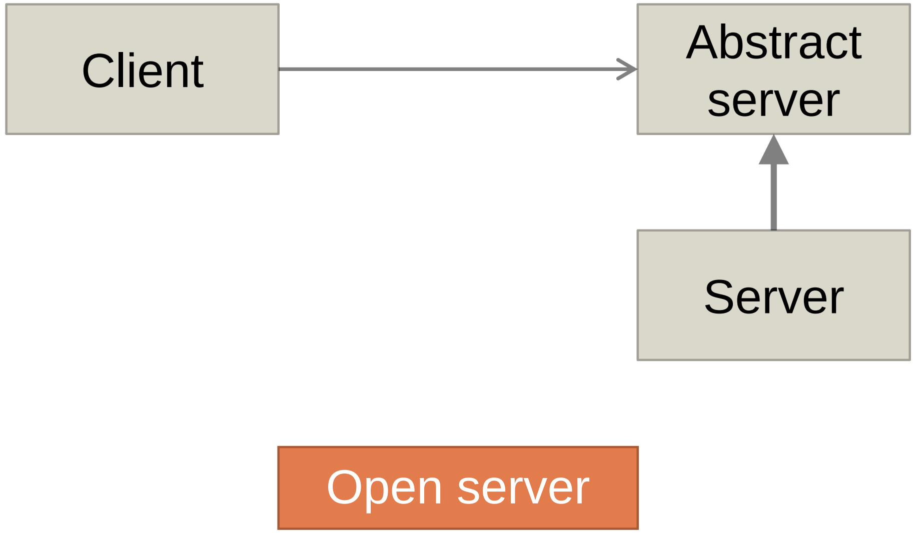
["Agile Software Development, Principles, Patterns, and Practices." Martin R. C. (2002)]

Does not conform to the open/closed principle



["Agile Software Development, Principles, Patterns, and Practices." Martin R. C. (2002)]

Strategy pattern



- Conforming to the open/closed principle
- Relies on abstractions
  - Interfaces
  - Abstract classes

["Agile Software Development, Principles, Patterns, and Practices." Martin R. C. (2002)]

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2.2. Antipatterns

[… tbc]

Liskov’s substitution principle (LSP)

"Let *q(x)* be a property provable about objects *x* of type *T*. Then *q(y)* should be provable for objects *y* of type *S* where *S* is a subtype of *T*."

[Barbara Liskov (1987)]

"Subtypes must be substitutable for their base types"

["Agile Software Development, Principles, Patterns, and Practices." Martin R C. (2002)]

- Child classes should never break the parent class' type definitions.
- All derived classes must be substitutable for their base classes.

- Substitutability
  - Child classes must **not:**
    - Remove base class behavior
    - Strengthen preconditions nor weaken post-conditions
    - Violate base class invariants
    - And in general, must not require calling code to know they are different from their base type
- This principle guides us in the creation of abstractions

Example: Violation of Liskov's Substitution Principle

```
class Rectangle {
  protected int m_width;
  protected int m_height;
  public void setWidth (int width) { m_width = width; }
  public void setHeight (int height) { m_height = height; }
  public int getWidth() { return m_width; }
  public int getHeight() { return m_height; }
  public int getArea() { return m_width * m_height; }
}
```

Postcondition: m_height does not change

Postcondition: m_width does not change

```
class Square extends Rectangle {
  public void setWidth (int width) {
      m_width = width;
      m_height = width;
  }
  public void setHeight (int height) {
      m_width = height;
      m_height = height;
  }
}
```

Violation of postcondition in super class!

Example: Violation of Liskov's Substitution Principle

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class Rectangle {
  protected int m_width;
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  public int getHeight() { return m_height; }
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Postcondition: m_height does not change

Postcondition: m_width does not change

```
class Square extends Rectangle {
  public void setWidth (int width) {
     m_width = width;
     m_height = width;
  }
  public void setHeight (int height) {
     m_width = height;
     m_height = height;
  }
}
```

```
class LspTest {
   private static Rectangle getNewRectangle() {
      return new Square();
   }

   public static void main (String args[]) {
      Rectangle r = LspTest.getNewRectangle();
      r.setWidth(5);
      r.setHeight(10);
      System.out.println(r.getArea());
   }
}
```

The area is 100 instead of 50!

The inheritance rules of OO languages are not sufficient

- OO inheritance relates to syntax only, not to semantics (pre- and post-conditions, invariants).
- The semantics of classes are not necessarily syntactic only. We may add behavior, e.g., in the form of pre- and post-conditions, or class invariants that hold before and after executing a method. Remember the discussion on semantic interfaces.
- Then we may require a subclass to **weaken preconditions** (not just contravariant argument types), to **strengthen postconditions** (not just covariant return types) and **establish invariants** that don't break the super class invariant. Liskov called this behavioral subtyping.
- Liskov's principle captures this idea (read the slide again!)

From requirements to system design

[… tbc]

Interface-segregation principle (ISP)

Clients should not be forced to depend upon interfaces they don't use.

["Agile Software Development, Principles, Patterns, and Practices." Martin R C. (2002)]

- Related to single responsibility principle
- Prefer small, cohesive interfaces to "fat" interfaces

Violation of ISP

```
interface IEmployee {
  public int calculateWorkHrs();
  public int getNoOfVacations();
}
```

```
class WiMi implements IEmployee {
  public int calculateWorkHrs() {
    // .... returns the work hrs
  }
  public int getNoOfVacations() {
    // ...... returns no of days in vacation sheet
  }
}
```

```
class HiWi implements IEmployee {
  public int calculateWorkHrs() {
    //.... returns the work hrs
  }
  public int getNoOfVacations() {
    throw new NotImplementedException();
  }
}
```

```
class Secretary {

  public List getAllEmployees() {
    // returns a list of hiwis and wimis
  }

  public void manageVacations() {
    List allEmployees = getAllEmployees();
    for(IEmployee emp : allEmployees) {
      int nov = emp. getNoOfVacations();
    }
  }
}
```

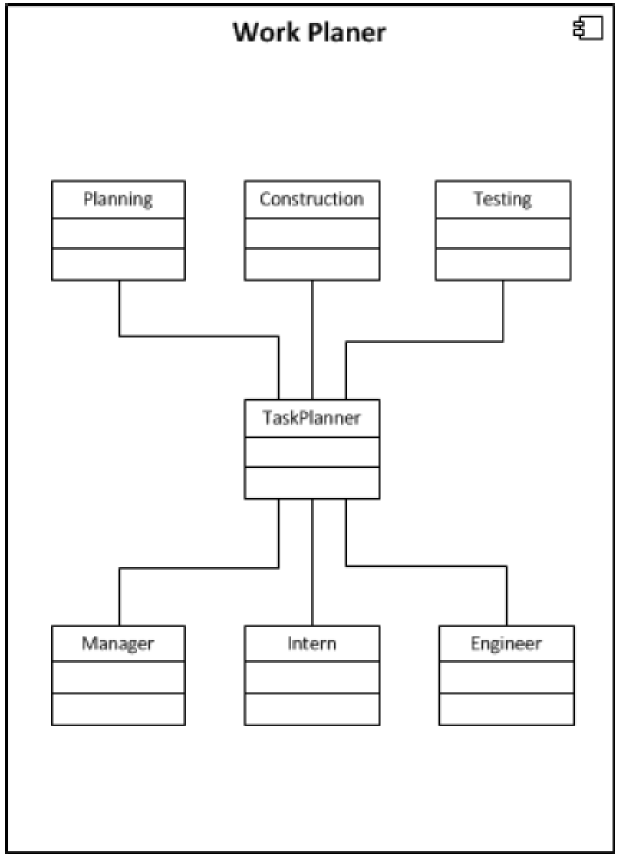
Flughafen gate, passanger repository, Boarding interface, managmeent interface, Passenger mgmt system; 2 folien good vs bad

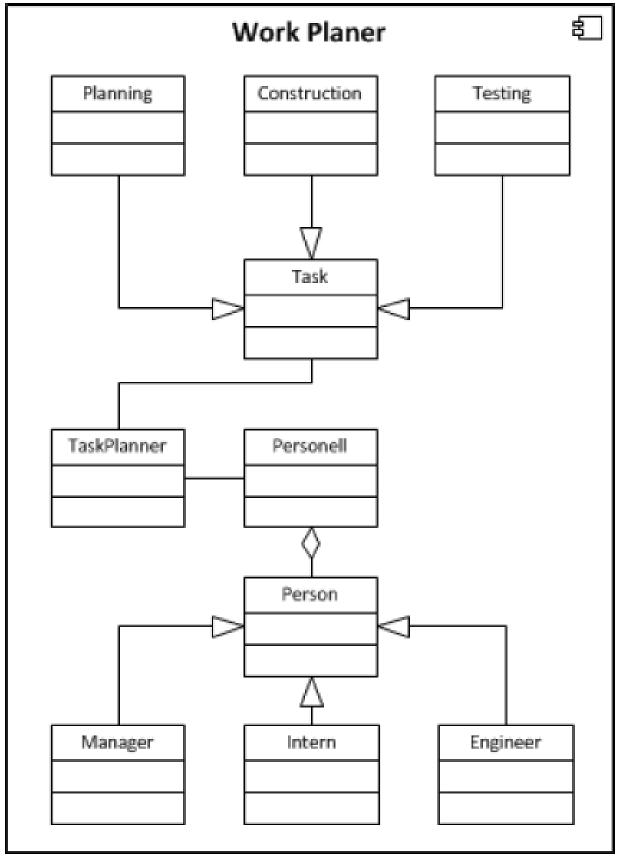
From requirements to system design

Anticipate change

- Build components in a way that minimizes effort for potential future changes.
- Find compromise between generality and specificity.
- Interface definition should consider potential extensions and changes.
- Low coupling and high cohesion ease changes.
- Don’t overdo it, though. Managed reuse is terribly difficult (and often terribly unsuccessful) – we’ll talk about product lines later.

Anticipate change





From requirements to system design

[… tbc]

Don't repeat yourself (DRY)

"Every piece of knowledge (and functionality) must have a single, unambiguous, authoritative representation within a system."

- Programmers are constantly in maintenance mode – the understanding of the system changes day by day.
- To perform maintenance, we have to change the representation of things.
- If you have more than one way to express the same thing, at some point the two or three different representations will fall out of step with each other.
- Redundant modules and interfaces that serve the same or almost the same purpose are problematic in terms of avoidable system complexity and ambiguity.
- Unnecessary repetition increases the risk of inconsistencies, increases maintenance effort, and reduces general understandability.

["The pragmatic programmer: from journeyman to master." Hunt A. and Thomas D. (2000)]

How does duplication arise?

- **Imposed** duplication
  - Developers feel they have no choice – the environment seems to require duplication.
- **Inadvertent** duplication
  - Developers don’t realize that they are duplicating information.
- **Impatient** duplication
  - Developers get lazy and duplicate because it seems easier.
- **Inter-developer** duplication
  - Multiple people on a team (on different teams) duplicate a piece of information.

Imposed duplication

- Multiple representations of information, e.g.:
  - Client-server application, using different languages on the client and server, both need to represent some shared structure on both.
  - Classes which mirror the schema of a database table.
  - A book which includes code samples which have to be compiled and tested.
  - Documentation in code
    - Keep low-level knowledge in the code, reserve the comments for other, high-level explanations.
  - Language issues: Many languages separate a module’s interface from its implementation, e.g.:
    - C and C++ header files, CORBA-IDL (the compiler helps here)

Have a single authoritative representation that then generates non-authoritative work products, like code or DDLs (data description languages).

Inadvertent duplication (1)

Bad design decisions

- Logistics example:
  - Trucks have a type, a driver, a license number
  - Delivery routes contain a driver, a truck, a route
  - If we encode the driver twice, then we need to change it twice, e.g., if a driver calls in sick.

Inadvertent duplication (2)

Comes as a result of mistakes in the design

```
class Line {
  Point start;
  Point end;
  double length;
}
```

Need to re-compute whenever start or end change

```
class Line {
  Point start;
  Point end;
  double length() {
    return start.distanceTo(end);
  }
}
```

No redundancy for length any more

```
class Line {
  private Point start;
  private Point end;
  private double length;
  private boolean changed = true;

  public void setStart(Point p) {
    start = p; changed = true;
  }
  public void setEnd(Point p) {
    end = p; changed = true;
  }
  public Point getStart() {
    return start;
  }
  public Point getEnd() {
    return end;
  }
  double getLength() {
    if(changed) {
      length = start.distanceTo(end);
      changed = false;
    }
    return length;
  }
}
```

But … caching for complex operations may be adequate

Impatient and inter-developer duplication

Impatient duplication arises due to:

- Time pressure → shortcuts
- It takes discipline and a willingness to spend time upfront to save pain later.

Inter-developer duplication can be avoided:

- Have a clear design, a strong technical project leader, and a well-understood division of responsibilities within the design.
- Encourage communication between developers.
- Have a central place in the source tree where utility routines and scripts can be deposited.
- Make a point of reading other people's source code and documentation (informally or during code reviews).
- Apply common sense!

Make it easy to reuse (reusability will be covered later in this lecture)
… oh, and don't overdo it!

From requirements to system design

[… tbc]

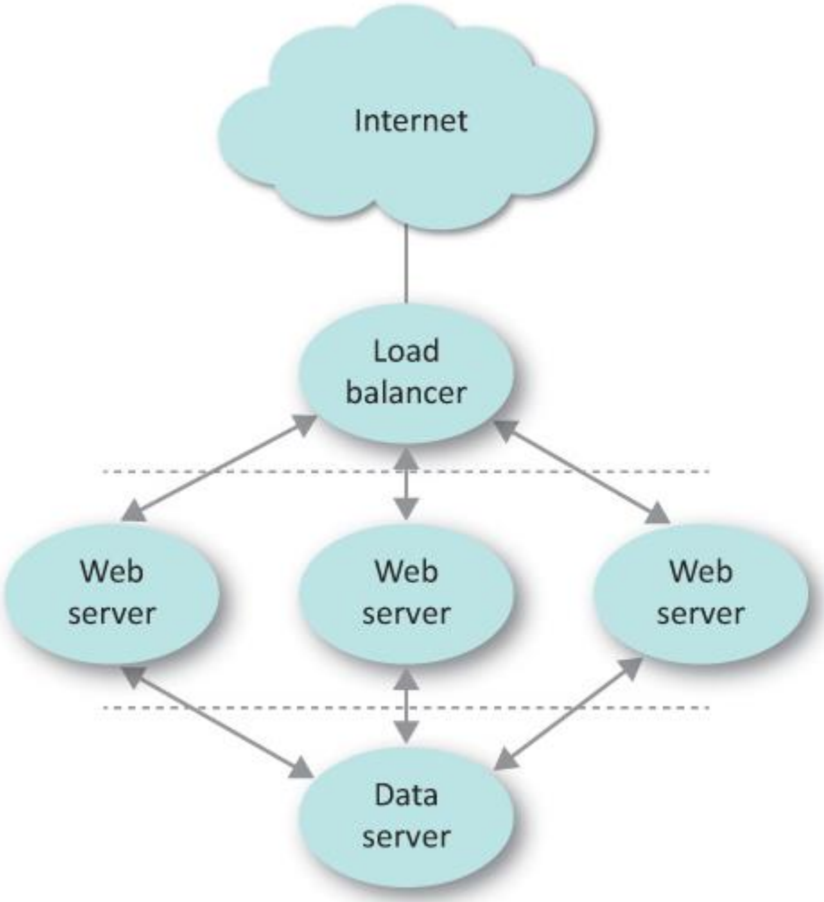
Back to the big picture

- Internal quality:
  - Modularity (positively) influences maintainability and reusability.
  - It also (both positively and negatively) influences testability – we will discuss this later.

- External quality:
  - We have seen that many layers may lead to many indirections, resulting in bad performance.
  - We have seen that a large attack surface makes a system vulnerable – architecture impacts security.

Architecture and security (1)

3- and 4-tier architectures



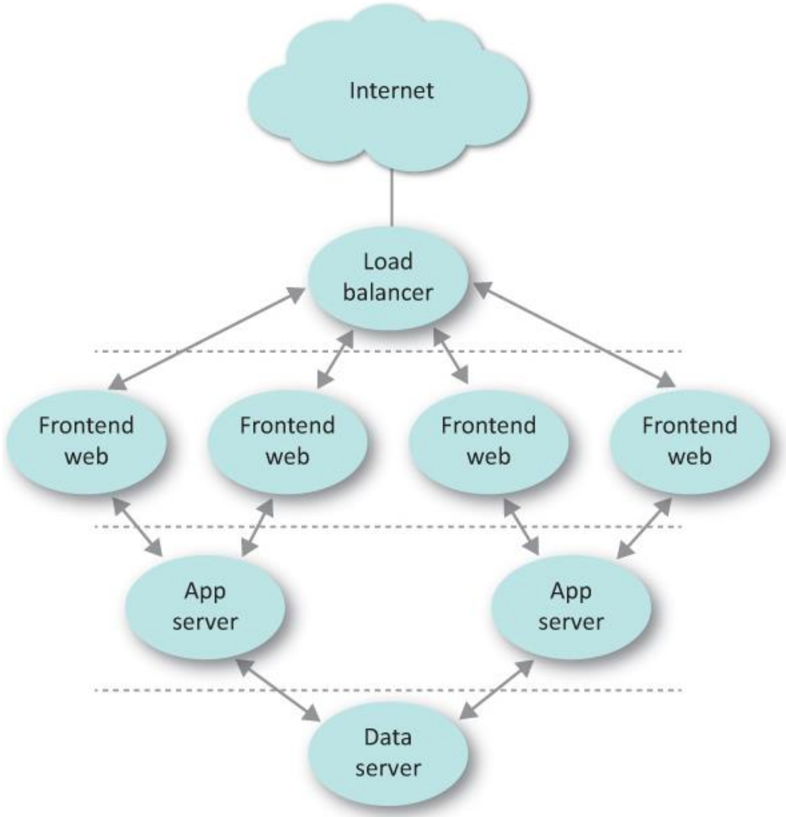
Limoncelli, T; Chalup, S.; Hogan, C.: **The Practice of Cloud System Administration: Designing and Operating Large Distributed Systems, Volume 2**
Addison-Wesley Professional, 2014

- 3 tiers
- Web server also runs application server
- Compromising web server facilitates (or is identical to) compromise of applications

+ efficient
+ "all in one hand"
- Rather large attack surface for applications

Architecture and security (2)

3- and 4-tier architectures



Limoncelli, T; Chalup, S.; Hogan, C.: **The Practice of Cloud System Administration: Designing and Operating Large Distributed Systems, Volume 2**
Addison-Wesley Professional, 2014

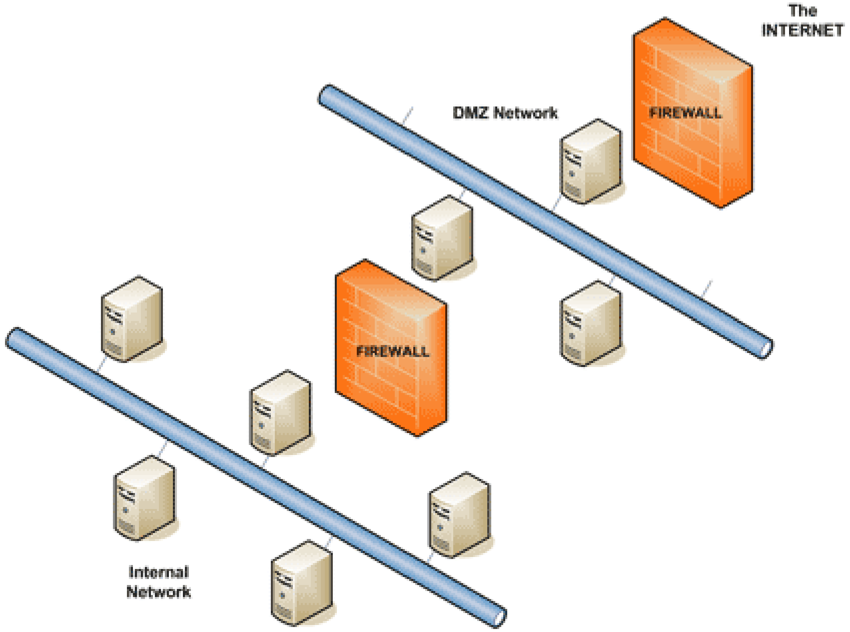
- 4 tiers
- Web and application servers separated
- Compromised web server only the first step to also compromise the applications

+ attack surface reduced

- Operations of web server and app server possibly in different hands

Architecture and security (3)

Demilitarized zones



http://www.techrepublic.com/article/solutionbase-strengthen-network-defenses-by-using-a-dmz/

- Idea: Separate internal network as much as possible from the hostile internet.
- DMZ is not as hostile as the internet.
- DMZ and internal network are two separate networks. Compromising a machine in the DMZ is not the same as compromising the internal network.
- Place public servers in the DMZ – and place internal machines in the internal network: Compromising them requires two steps.

Example: Tradeoffs

- Problem description
  - Semi-automated surveillance and burglary detection
  - Houses with wireless sensors and wired cameras
  - Cameras can be monitored by customers
  - Not all alarms are actual burglary attempts
  - Notification of security personnel in cases of emergency
  - Customers and security officers use mobile clients
  - Security service company serves multiple customers

Requirements

Key functional requirements:

- System must **aggregate** sensor and camera **measurements**
- System must **detect emergency situations**
- System must **notify security personnel** in case of emergency
- System must be **accessible through mobile devices**
- System can be **monitored by customers**

Key non-functional requirements:

- The system must be **secure** and **reliable**
- The system must be **scalable**
- The system must be **privacy-preserving**
- The system communication must be **fast** and **cost-efficient**

A little software architecture example (1)

So… what do we make out of this?

- Need to make requirements more precise and ideally ***measurable***
- Need to map functional requirements to components
- Mapping must satisfy non-functional constraints
- Need to balance conflicting requirements and goals
- Need to be aware of conflicts and dependencies

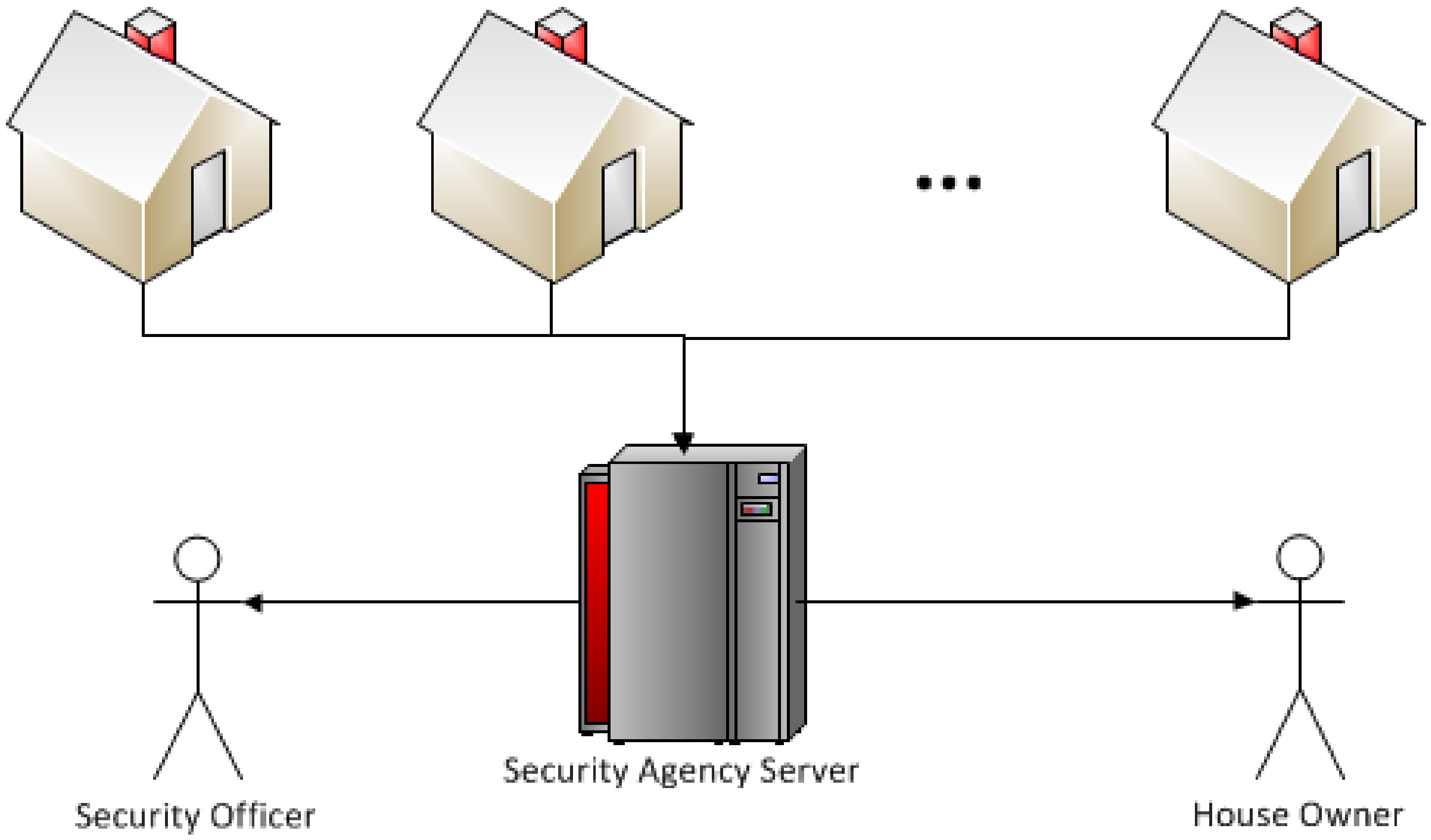
A little software architecture example (2)

So… what do we make out of this?

- Infinitely many architectural alternatives
- Alternatives vary in quality of requirement satisfaction
- Hard if not impossible to satisfy all requirements
- There is no perfect solution!
  → Need to prioritize and find compromises

- Let’s analyze some examples…

Context view

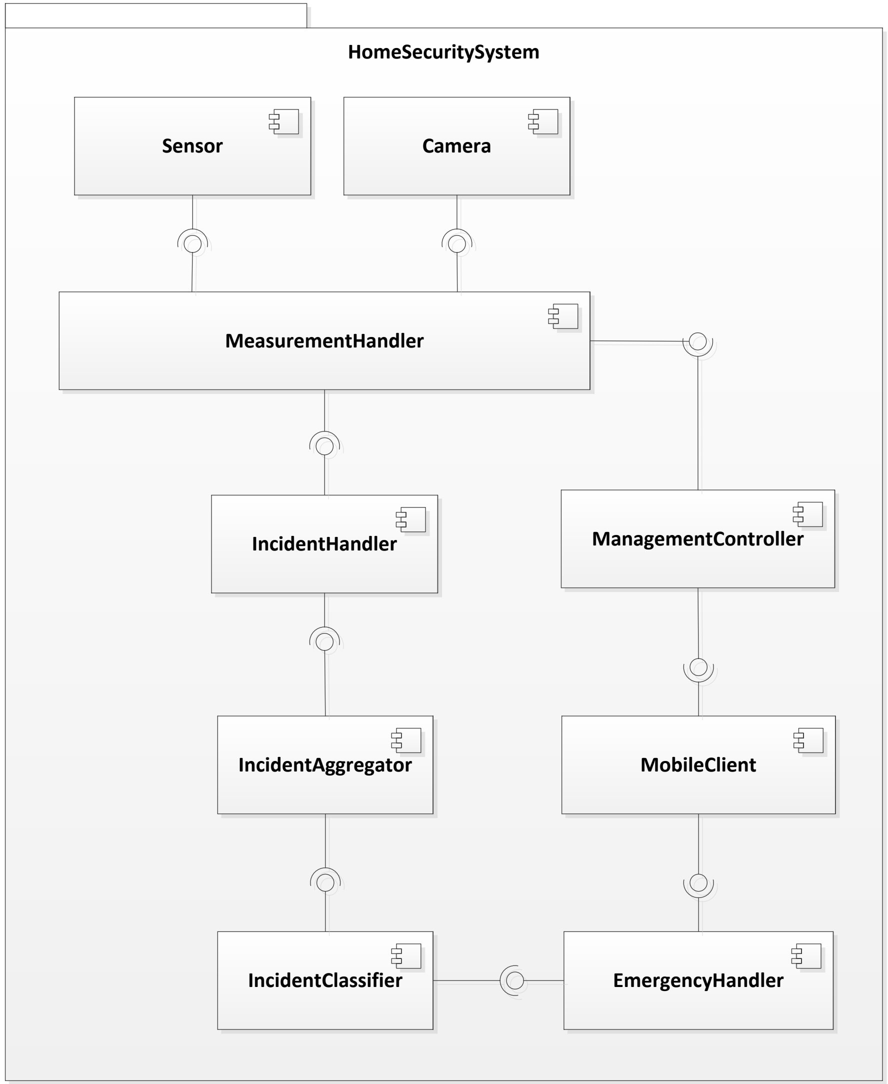


Component-and-connector view

Alternative A

- Decomposition is not deployment-oriented

- Rather tight coupling
  → scalability (-)
  → portability (-)
  → maintainability (-)
  → efficiency (+)

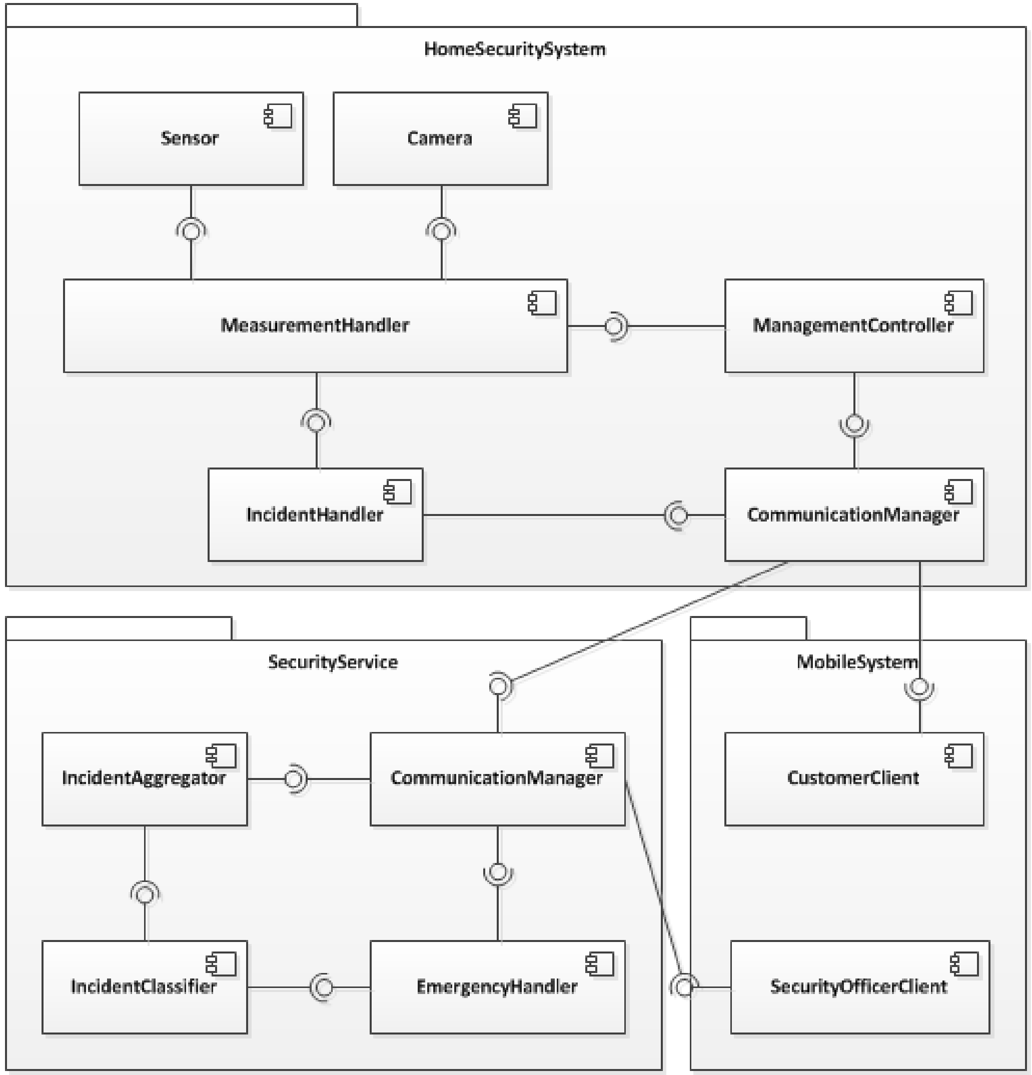


Component-and-connector view

Alternative B

Decomposition is deployment-oriented

→ scalability (+)
→ portability (+)
→ maintainability (+)
→ efficiency (-)

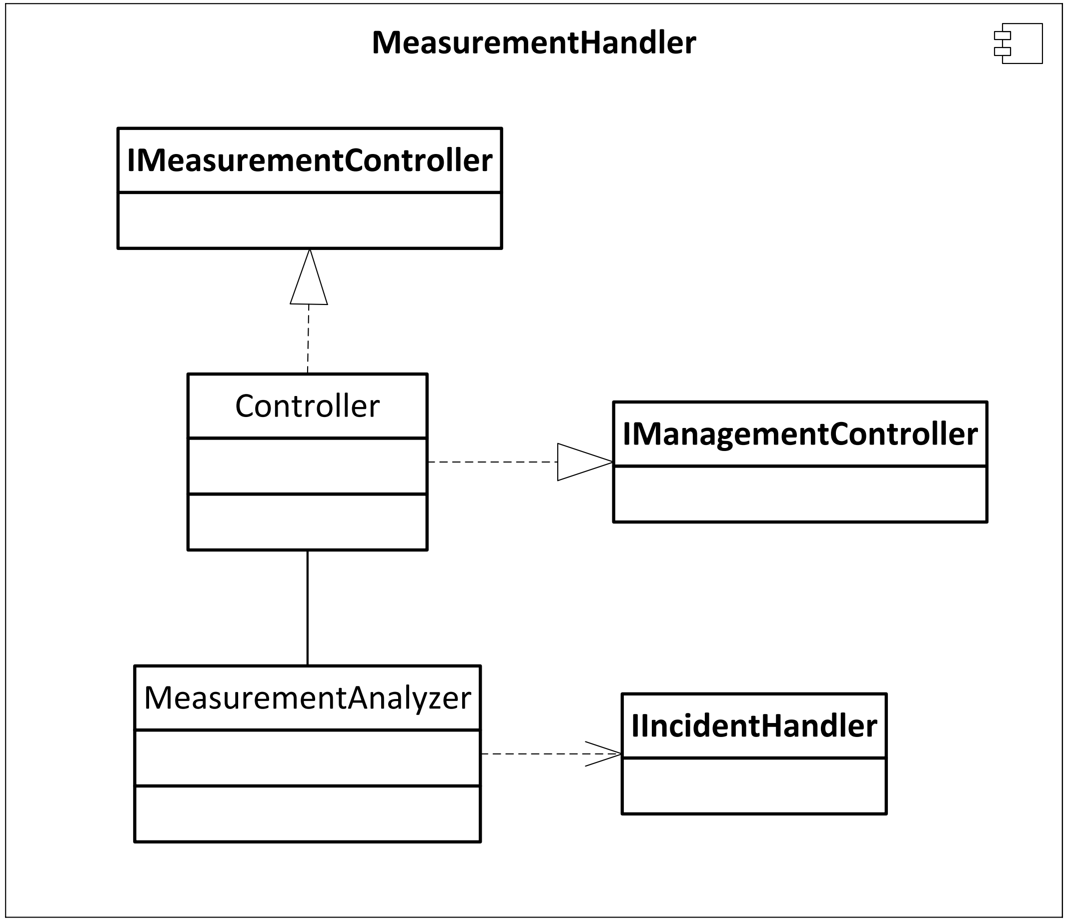


Module view

Alternative A

- Very simple structure
- Two “magic-classes”

- Barely decomposed
  → portability (-)
  → maintainability (-)
  → efficiency (+)

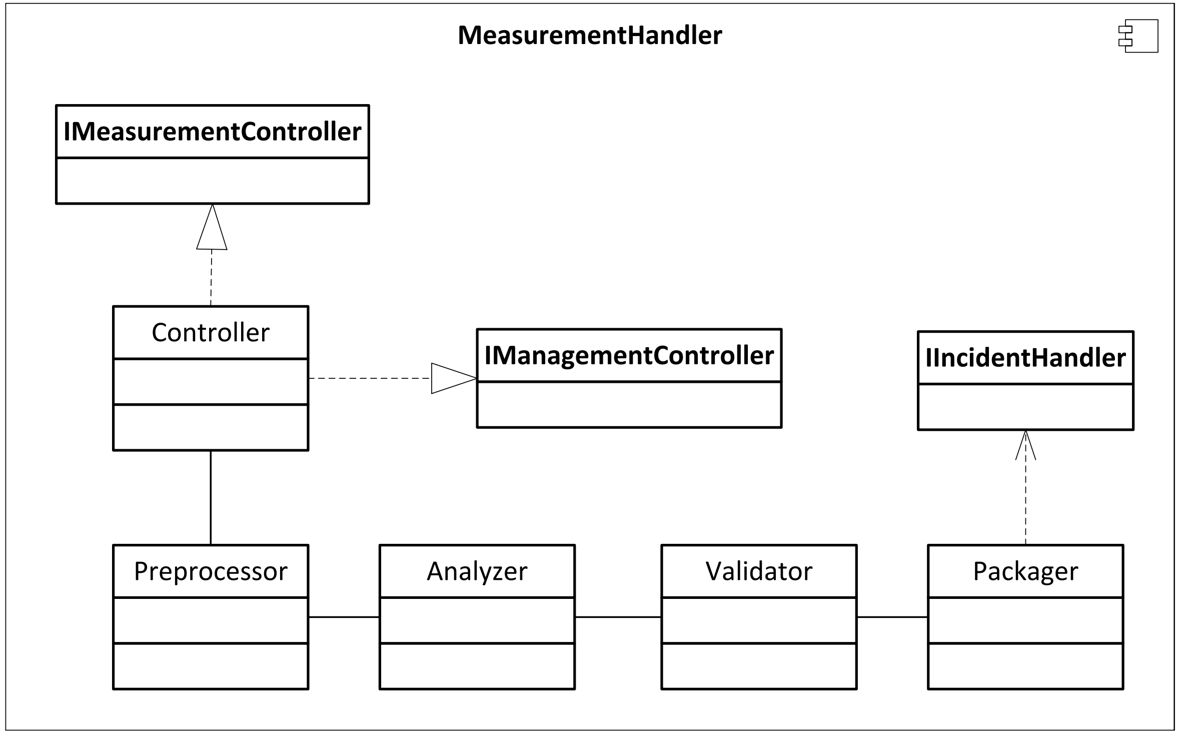


Module view

Alternative B

- Sequential processing
  → efficiency (+)

- Separation of concerns
  → scalability (+)
  → maintainability (+)

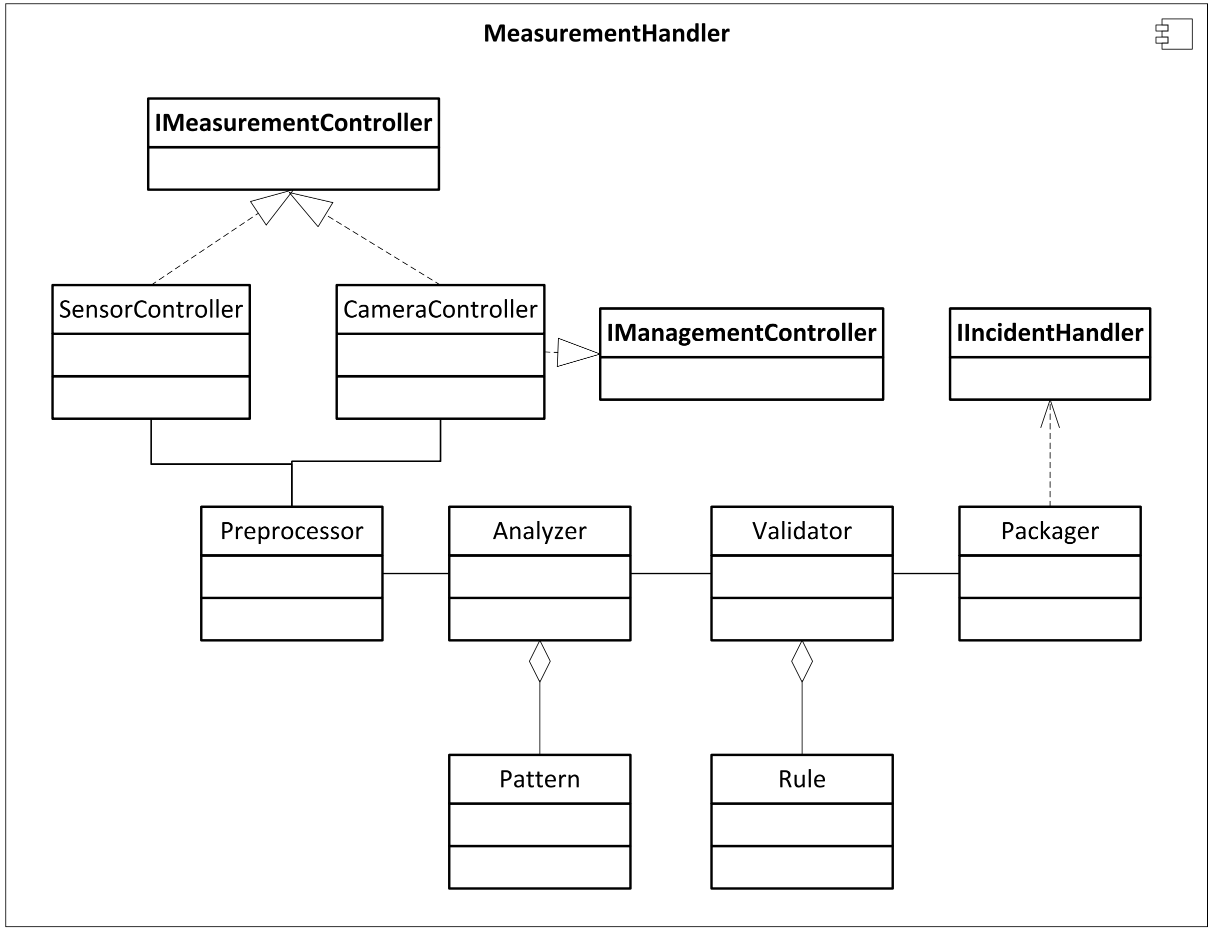


Module view

Alternative C

- Generic measurement controllers
  → maintainability (+)

- Pattern- and rule-aggregations
  → portability (+)
  → scalability (+)



Allocation view