Software Engineering for HPC - Notes

260236

April 2024

Preface

Every theory section in these notes has been taken from two sources:

None

About:

GitHub repository

Contents

1	\mathbf{Intr}	roduction	4
	1.1	The importance of software engineering	4
	1.2	Software engineering: definition	5
	1.3	The software product and the process	6
		1.3.1 ISO/IEC 25010	6
		1.3.2 Productivity	6
		1.3.3 Timeliness	7
	1.4	Software Lifecycle	8
		1.4.1 Waterfall model	8
2	\mathbf{HP}	C Software, Relevant Qualities and Systems Engineering	
	Met	thods	10
	2.1	High Performance Computing Software	10
	2.2	Relevant Qualities	12
	2.3	Systems Engineering Methods	14
3		quirement Engineering	15
	3.1	Definition	15
	3.2	Studying the interplay between the world and the machine	16
		3.2.1 Completeness of Requirements	18
	3.3	Formulating and classifying requirements	19
	3.4	Eliciting requirements	21
4	Soft	rwone Design	26
4		cware Design	26
4	4.1	Software Architecture	26
4	4.1 4.2	Software Architecture	26 27
4	4.1	Software Architecture	26 27 28
4	4.1 4.2	Software Architecture	26 27 28 28
4	4.1 4.2	Software Architecture	26 27 28 28 29
4	4.1 4.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure)	26 27 28 28 29 30
4	4.1 4.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure)	26 27 28 28 29 30 31
4	4.1 4.2 4.3	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure)	26 27 28 28 29 30 31 32
4	4.1 4.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure)	26 27 28 28 29 30 31
	4.1 4.2 4.3	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles	26 27 28 28 29 30 31 32 33
5	4.1 4.2 4.3 4.4 Arc	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles	26 27 28 28 29 30 31 32 33
	4.1 4.2 4.3 4.4 Arc 5.1	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition	26 27 28 28 29 30 31 32 33 36
	4.1 4.2 4.3 4.4 Arc	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server	26 27 28 28 29 30 31 32 33 36 36
	4.1 4.2 4.3 4.4 Arc 5.1	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design	26 27 28 28 29 30 31 32 33 36 36 37 37
	4.1 4.2 4.3 4.4 Arc 5.1	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design 5.2.2 Error handling, multiple interfaces and interface evolution	26 27 28 28 29 30 31 32 33 36 36 37 37 38
	4.1 4.2 4.3 4.4 Arc 5.1 5.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design 5.2.2 Error handling, multiple interfaces and interface evolution 5.2.3 Handling multiple requests	26 27 28 28 29 30 31 32 33 36 36 37 37 38 39
	4.1 4.2 4.3 4.4 Arc 5.1	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design 5.2.2 Error handling, multiple interfaces and interface evolution 5.2.3 Handling multiple requests Three-Tier Architecture	26 27 28 28 29 30 31 32 33 36 36 37 37 38 39 42
	4.1 4.2 4.3 4.4 Arc 5.1 5.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design 5.2.2 Error handling, multiple interfaces and interface evolution 5.2.3 Handling multiple requests Three-Tier Architecture 5.3.1 N-tier architecture	26 27 28 28 29 30 31 32 33 36 36 37 37 38 39 42
	4.1 4.2 4.3 4.4 Arc 5.1 5.2	Software Architecture Architecture and multiple structures Software design descriptions and UML 4.3.1 Component Diagram (C&C structure) 4.3.2 Sequence Diagram (C&C structure) 4.3.3 Class Diagram (module structure) 4.3.4 Package Diagram (module structure) 4.3.5 Deployment Diagram (allocation structure) Design principles hitectural styles Definition Client-Server 5.2.1 Interface design 5.2.2 Error handling, multiple interfaces and interface evolution 5.2.3 Handling multiple requests Three-Tier Architecture	26 27 28 28 29 30 31 32 33 36 36 37 37 38 39 42

1 Introduction

1.1 The importance of software engineering

Software engineering is so important because it is everywhere. Our society is now totally dependent on software-intensive systems. Think about it. The society could not function without software, for example:

- Transportation systems;
- Energy systems;
- Manufacturing systems.

For these reasons, software failures cannot be tolerated.

In the following list, we can see some famous software issues:

• 911 Outage on April 2014. On 10th April 2014, Washington State had no 911 service for six hours. A software issue causes this event. The software dispatching the calls had a counter used to assign a unique identifier to each call. The counter went over the threshold defined by developers. All calls from that moment on were rejected.

More info is here.

• Ariane 5, 1996. On 4th June 1996, forty seconds after take off, Ariane 5 broke up and exploded. The total cost for developing the launcher has been 8000 million dollars. The launcher contained a cluster of satellites for 500 million dollars. Again, the explosion was caused by software failure.

More info is here: accident tech report and video.

1.2 Software engineering: definition

There are some fields of computer science dealing with software systems:

- Large and complex;
- Built by teams;
- It exists in many versions;
- Last many years;
- Undergo changes.

In each field, a software engineer needs to have some skills. In contrast to a programmer that has the following abilities:

- They develop a complete program;
- They work on known specifications;
- They work individually.

A software engineer has the following skills:

- **Identifies** requirements and develops specifications;
- **Designs** a component to be combined with other components, developed, maintained, and used by others; component can become part of several systems;
- Works in a team.

We can <u>summarize</u> the skills of a software engineer as follows:

- Technical
- Project management
- Cognitive
- Enterprise organization
- Interaction with different cultures
- Domain knowledge

The main goal of a software engineer is to develop software products. Not only is the product significant, but the process is also fundamental. The quality of the process affects the quality of the product.

1.3 The software product and the process

The product developed by a software engineer differs from traditional product types. It isn't easy to describe and evaluate because it is intangible. Some aspects affecting the product quality:

- Development technology;
- Process quality;
- People quality;
- Cost, time and schedule.

1.3.1 ISO/IEC 25010

An ISO (International Organization for Standardization) called $ISO/IEC\ 25010$ comprises the nine quality characteristics:

SOFTWARE PRODUCT QUALITY									
FUNCTIONAL SUITABILITY	PERFORMANCE EFFICIENCY	COMPATIBILITY	INTERACTION CAPABILITY	RELIABILITY	SECURITY	MAINTAINABILITY	FLEXIBILITY	SAFETY	
FUNCTIONAL COMPLETENESS FUNCTIONAL CORRECTNESS FUNCTIONAL APPROPRIATENESS	TIME BEHAVIOUR RESOURCE UTILIZATION CAPACITY	CO-EXISTENCE INTEROPERABILITY	APPROPRIATENESS RECOGNIZABILITY LEARNABILITY OPERABILITY USER ERROR PROTECTION USER ENGAGEMENT INCLUSIVITY USER ASSISTANCE SELF- DESCRIPTIVENESS	FAULTLESSNESS AVAILABILITY FAULT TOLERANCE RECOVERABILITY	CONFIDENTIALITY INTEGRITY NON-REPUDIATION ACCOUNTABILITY AUTHENTICITY RESISTANCE	MODULARITY REUSABILITY ANALYSABILITY MODIFIABILITY TESTABILITY	ADAPTABILITY SCALABILITY INSTALLABILITY REPLACEABILITY	OPERATIONAL CONSTRAINT RISK IDENTIFICATION FAIL SAFE HAZARD WARNING SAFE INTEGRATION	

Figure 1: ISO/IEC 25010

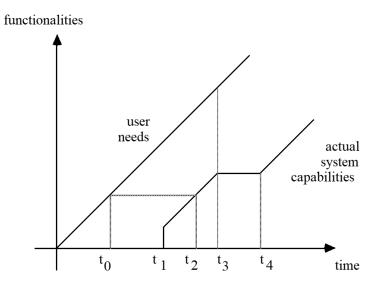
1.3.2 Productivity

A process quality to consider is **productivity** (the **process of producing a product**). The definition can be: "ability to produce a good amount of product". To **measure it**, we can use **delivered items by unit of effort**, where:

- Delivered items: lines of code (and variations) function points;
- Unit of effort: person month (note: persons and months cannot be interchanged).

1.3.3 Timeliness

Another process quality to consider is timeliness. The definition is: "the ability to respond to change requests in a timely fashion".



As you can see by the graph, the "user needs" is a linear function (and sometimes can be exponential!). A software engineer should be able to respond to the client's requests as soon as possible. As the graph shows, a request made on time t_0 is completed on time t_2 ; but another request can be made at that time, and so on. The actual system capabilities can't grow up always because sometimes there are "brainstorming times" to increase product quality (ISO/IEC 25010).

1.4 Software Lifecycle

Initially, no reference model is inside a software lifecycle: code and fix (or refactoring). However, a traditional waterfall model is chosen to react to the many problems that a software engineer faces.

1.4.1 Waterfall model

The waterfall model is a breakdown of development activities into linear sequential phases, meaning they are passed down onto each other, where each phase depends on the deliverables of the previous one and corresponds to a specialization of tasks. [1] Its organization is the following:

- High phases:
 - Feasibility Study: this is a cost-benefit analysis.

The *main goal* is determining whether the project should be started (e.g. buy or make), possible alternatives, and needed resources.

The *outcome* is a **feasibility study document**. This paper provides:

- * A preliminary problem description;
- * Some scenarios describing possible solutions;
- * Costs and schedules for the different alternatives.
- Requirements Analysis and Specification: this is an analysis of the domain in which the application takes place.

The *main goal* is to identify requirements and derive specifications for the software. Note these specifics require a (continuous) interaction with the user and an understanding of the properties of the domain.

The *outcome* is a particular document called **Requirements Analysis and Specification Document** (RASD).

Design: this is the definition of the software architecture.
 There, the definition of components (modules) and the relations/interactions among these components.

The *main goal* is to support the concurrent development of separate responsibilities.

The *outcome* is a summary of this info in a **design document**.

- Low phases:
 - Coding and Unit Test: each module is implemented using the chosen programming language. Furthermore, each module is tested in isolation by the module developer. Also, the programs should include their documentation.
 - Integration and System Test: the modules are integrated into (sub)systems. The integrated (sub)systems are tested. Follows an incremental implementation scheme. A complete system test is needed to verify the overall properties. Note that sometimes we have alpha test and beta test.

- Deployment: is the process used to conceive, specify, design, program, document, test, and bug fix to create and maintain applications, frameworks, or other software components.
- Maintenance: the maintenance is divided into two types:
 - * Corrective deals with the repair of faults or defects found.
 - * Evolution is also divided into three types:
 - · Adaptive maintenance: consists of adapting software to changes in the environment (the hardware or the operating system, business rules, government policies).
 - · *Perfective* maintenance: mainly deals with accommodating new or changed user requirements.
 - · Preventive maintenance: concerns activities aimed at increasing the system's maintainability.

A Problems derived from correction and evolution

Note: the distinction between correction and evolution can be unclear because specifications often must be completed and clarified. This causes problems because specs are usually part of a developer and customer contract.

- Early frozen specs can be problematic because they are more likely to be wrong.
- Another problem is **software evolution** because **it is never anticipated or planned**. Since the software is easy to change, often, under emergency, changes are applied directly to code, and consequently, the state of project documents is inconsistent.

✓ Solutions - Best practices

Some good engineering practices exist to solve the evolution problem: first, modify the design, then change implementation and apply changes consistently in all documents. Also, the software must be designed to accommodate changes cost-effectively. This is one of the main goals of software engineering.

✓ Flexible processes

We can make the waterfall model more flexible. In this case, the main goal is to adapt to changes (especially in requirements and specs). The idea is that the stages are not necessarily sequential, and processes become iterative and incremental.

2 HPC Software, Relevant Qualities and Systems Engineering Methods

2.1 High Performance Computing Software

There's no single definition of HPC, but it can be explained in a number of ways:

Definition 1

The practice of aggregating computing power in a way that delivers much high performance than one could get out of a typical desktop computer or workstation to solve large problems in science, engineering, or business.

Thousands of processors working in parallel to analyze billions of pieces of data in real time, performing calculations thousands of times faster than a normal computer.

The use of parallel processing for running advanced, large-scale application programs efficiently, reliably and very quickly on supercomputer systems.

The platform technology concerned with programming for performance, where performance takes the broad meaning of:

- Speed (reducing time to solution);
- Energy efficiency (doing more with less power);
- Upscaling (handling larger problems such as simulating a wing aand then a full plane, or a cell and then an organ);
- High throughput (the ability to handle large volumes of data in near real-time, as required in the financial services industry, telecoms or satellite imagery).

As **Parallel and Distributed Computing (PDC)** exist, it is necessary to explain the difference. The main characteristics of PDC are:

- Concurrency: it is a property of software. A piece of software is also concurrent if it can have more than one active execution context.
- Parallelism: it is a property of software. The execution of different tasks/pieces of software at the same time.
- Distribution. The execution of different tasks/pieces of software on physically distinct computing nodes connected through a network, lack of a global clock.

PDCs are multi-core machines, whereas HPCs are quantum computers. However, both share parallel machines, HPC clusters and cloud infrastructures.

There are **two categories** of HPC software:

- Compute-intensive applications. These are complex calculations that require a large number of computing resources. They also often require parallel computing.
- Data-intensive applications. They focus on processing, storing and retrieving large amounts of data. Typically built as distributed systems to ensure reliability and scalability.

2.2 Relevant Qualities

For the two categories explained, there are some important characteristics:

- For Compute-intensive applications:
 - Correctness: the software is correct if it satisfies the specifications, but be careful! Sometimes, modelling reality into a model (using the specifications) isn't the bigger problem. Instead, it is difficult or impossible to show actual correctness concerning reality. For example, imagine you are building a simulator of a planet lander before you have ever visited it.
 - How can you fix this issue? We can check that the software output fulfils the important desired properties and identify and apply a measure of accuracy.
 - Performance: it is the efficient use of resources. Again, be careful! Is it a good idea? Is performance improvement always a good idea? Because it is not necessarily if:
 - * It makes software more difficult to read and maintain
 - * It reduces the portability of software
 - Portability.
 - Maintainability. A system can have this feature if it follows three principles:
 - 1. Operability: make it easy for the operations team to run the system and keep it running. There are a number of things that need to be done to achieve this:
 - * Provide visibility into the runtime behavior and internals of the system, with good monitoring.
 - * Provide good support for automation and integration with standard tools.
 - * Avoidance of dependencies on individual machines (allowing machines to be taken down for maintenance while the system as a whole continues to run uninterrupted).
 - * Provide good documentation and an easy to understand operational model ("If I do X, Y will happen").
 - * Provide good default behavior, but also give administrators the freedom to override defaults when necessary.
 - * Self-healing when appropriate, but also giving administrators manual control over system state when needed.
 - 2. Simplicity: make it easy for other software engineers to understand the system. This is necessary because complex systems take more time to understand and increase the cost of maintenance. There are several techniques for doing this:
 - * Reducing accidental complexity.
 - * Using abstractions, such as organising the architecture into well-defined components that hide the internal complexity behind a clear and easy-to-use interface; or reusing known solutions.

- 3. **Evolvability**: make it easy for engineers to change the system as new requirements emerge. There are a number of things that need to be done to achieve this:
 - * Organize your development process to cope with evolution.
 - * Keep track of how requirements are mapped to your software structure.
 - * Update documentation.
 - * Continue to ensure simplicity and operability.
- For Data-intensive applications:
 - Reliability: can be mathematically defined as probability of absence of failures for a certain period. The typical expectations are:
 - * The application performs the expected function
 - * It can tolerate mistakes by users
 - * It prevents unauthorized access and abuse
 - Scalability: the system ability to cope with increased load. The load unit depends on the product: for web apps can be represented with the number of requests per second; for databases can be the number of read and write operation (or their ratio).
 - Maintainability. Same as above.

In the software, there can be some errors, but a software engineer should be able to recognize the type of failure, faults or defects:

- A defect is an imperfection or deficiency in a work product where that work product does <u>not meet its requirements or specifications</u> and needs to be either repaired or replaced.
- A defect encountered during software execution is a fault (a fault is a subtype of defect, and can be of two types, see below).
- A system failure can be:
 - Termination of the ability of a product to perform a required function or its inability to perform within previously specified limits.
 - An event in which a system or system component does not perform a required function within specified limits.

There are some exceptions where systems are fault-tolerant or resilient. These are systems that can cope with faults and prevent faults from occurring. An advantage of fault-tolerance is that reliability is increased.

The **fault** can be of **two types**:

• Hardware Faults.

A Description of the problem

It is a defect encountered during hardware execution. In a large datacenter these can happen on a daily basis. Different pieces of hardware usually fail independently from each other.

✓ Possible solutions

The possible solutions are two: hardware redundancy and software fault-tolerance techniques.

• Software Faults.

A Description of the problem

They result from **software development errors**. Can stay dormant for a long time and appear suddenly. They can **determine failures in multiple components** at the same time.

✓ Possible solutions

There is no single solution! It is a combination of strategies. So use defensive programming, by testing before release and during operation:

- Reboot the system frequently (rejuvenation)
- Continuous monitoring and alerting in case of possible symptoms
- Deliberately introduce failures to train the fault tolerance machinery (chaos engineering)

2.3 Systems Engineering Methods

There are several systems engineering methodologies required in High Performance Computing:

- Modelling the software structure and checking its properties.
- Performance analysis and improvement.
- Source code management.
- Documentation, standards, support to maintainability.
- Support to scalability.
- Attention to operability and automation.

3 Requirement Engineering

3.1 Definition

Before the definition, we give a possible scenario to understand what requirement engineering is.

The municipality of Milan says the following: "The time it takes to make decisions on building permits for residential buildings in the city is too long. We want to develop software that will help us reduce this time". So where do we start? How do we identify the most important aspects? How do we make sure that we have understood what our customers want from us?

Definition 1

Software measure engineering (**Requirement Engineering**) is the process of discovering the purpose for which the software is intended by identifying stakeholders and their needs, and documenting these in a form suitable for analysis, communication and subsequent implementation.

The questions derived from requirements engineering are:

- Identify stakeholders
- Identify their needs
- Produce documentation
- Analyze, communicate, implement requirements

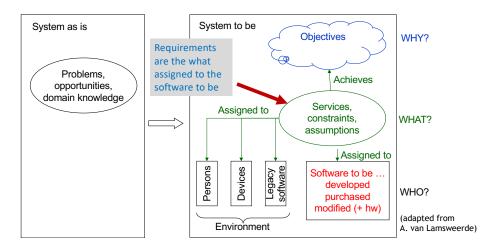


Figure 2: Analyzing the system as is and the system to be.

3.2 Studying the interplay between the world and the machine

Example 1: ambulance dispatching system

For every urgent call reporting an incident, an ambulance should arrive at the incident location within 14 minutes. For every urgent call, details about the incident are correctly encoded.

When an ambulance is dispatched, it will reach the incident location in the shortest possible time. Accurate ambulance locations are known by GPS. Ambulance crews correctly notify ambulance availability through a mobile data terminal.

Given the previous problem, are you able to extract requirements from this description? Some possible questions might be:

- Should the software system drive the ambulance?
- Who or what will "correctly encode" details about incidents?
- Do terminals already exist or not?

And more in general:

- What are the boundaries of the system? What is inside/outside? What is in-between?
- How do we think about these aspects in a systematic way?

This example is necessary to understand the **phenomena of world and machine**. The **machine** is the part of the system to be developed (typically a software-to-be and a hardware). The **world** (or environment) is the part of the real world that is affected by the machine.

Requirements engineering is **concerned with the phenomena that occur** in **the world**. In the previous **example**, RE is concerned with the following phenomena:

- Occurrence of incidents
- Reports of incidents by public calls
- Encoding of call details into dispatching software
- Assignment of an ambulance
- Arrival of an ambulance at the scene of an incident

But RE is also interested in the phenomena that occur inside the machine. In the previous example

- The creation of a new object of the class Incident
- The updating of a database entry

Requirements models are models of the world!

Using the **example** on the previous page, we can show the phenomena we are interested in the world or in the machine set.



Figure 3: The world and the machine sets, with reference to example on page 16.

More generally, we can divide the machine and the world sets as:

- The world which have goals and domain properties;
- The machine which have computers and programs;
- The requirements which is the bridge between the world and the machine.



Figure 4: Goals, domain properties, requirements, computers and programs.

We explain more detailed these value inside the two sets:

- Goals are prescriptive assertions formulated in terms of world phenomena (not necessarily shared)
- Domain properties (or assumptions) are descriptive assertions assumed to hold in the world
- Requirements are prescriptive assertions formulated in terms of shared phenomena

Using the example on the page 16, we can identify the goal, the domain assumptions and the requirement as follows:

• Goal: For every urgent call reporting an incident, an ambulance should arrive at the incident scene within 14 minutes.

• Domain assumptions:

- For every urgent call, details about the incident are correctly encoded.
- When an ambulance is mobilized, it will reach the incident location in the shortest possible time.
- Accurate ambulances' location are known by GPS.
- Ambulance crews correctly signal ambulance availability through mobile data terminals on board of ambulances.
- Requirement: When a call reporting a new incident is encoded, the Automated Dispatching Software should mobilize the nearest available ambulance according to information available from the ambulances' GPS and mobile data terminals.

3.2.1 Completeness of Requirements

Given the set of requirements \mathbf{R} , goals \mathbf{G} and domain assumptions \mathbf{D} .

Definition 2

We say that \mathbf{R} is **complete** if and only if:

$$\mathbf{R}$$
 and $\mathbf{D}\mid =\mathbf{G}$

We can make an analogy with program correctness. A program P running on a particular computer C is correct if it satisfies the requirement R: P and C \mid = R.

- G captures all the stakeholders' needs.
- D represents valid properties/assumptions about the world.

3.3 Formulating and classifying requirements

The requirements can be of three types:

- Functional requirements: describe the interactions between the system and its environment (independent from implementation). In other words, are the main (functional) goals the software has to realize.
 - For example: "the word processor shall allow users to search for strings in the text"; "the system shall allow users to reserve taxis".
- Non-functional requirements (NFRs): further characterization of user-visible aspects of the system not directly related to functions.
 - For example: "the response time must be less than 1 second"; "the server must be available 24 hours a day".
- Constraints requirements: imposed by the customer or the environment in which the system operates.
 - For example: "the implementation language must be Java"; "the credit card payment system must be able to be dynamically invoked by other systems relying on it".

We make some observations about non-functional requirements. NFRs predicate on **external** non-functional qualities, and these qualities must be **measurable by metrics**. NFRs have some characteristics:

- Constraints on how functionality must be provided to the end user.
- The application domain determines their relevance and their prioritization.
- Have a strong influence on the structure of the system to be built. For example, a system may require 24/7 availability. As a result, it is likely to be designed as a replicated system (with redundant components).

Example 2: are these requirements?

1. "The user should insert correct information in the enrolment form".

This is not a requirement! How can the software prevent a user from entering incorrect information? Specifically, is a domain assumption!

2. "The system should check whether fiscal code are well formed".

Yes, the software can do this! So it is a requirement.

Example 3: types of requirements

Example of functional requirements:

- "The system shall allow users to reserve taxis".
- "The system should never allowe non-registered users to see the list of other users willing to share a taxi".

• "The system should guarantee that the reserved taxi picks the user up".

But attention! There is **unfeasible** (from the perspective of the software to be) **functional requirements**:

• "The system should guarantee that the reserved taxi picks the user up".

This is because the software cannot guarantee this feature! Example of **non-functional requirements**:

- $\bullet \ "The \ system \ has \ to \ provide \ a \ feedback \ in \ 5 \ seconds".$
- "The system should be available 24/7".

Example of technical requirements:

- "The system should be implemented in Java".
- "The search for the available taxi should be implemented in class Controller".

Example 4: bad requirements

1. "The system shall process all mouse clicks very fast to ensure users do not have to wait".

The problem here is that it **cannot be verified (tested)**, because what does "fast" mean? Do we have a metric? Can you quantify it?

2. "The user must have Adobe Acrobat installed".

The problem here is that it **cannot be achieved by the software system itself**. It is not something that the system has to do. <u>But</u> it could be expressed as a domain assumption, so it is not a functional requirement for our software.

3.4 Eliciting requirements

The Requirements Elicitation is the practice of researching and discovering the requirements of a system from users, customers, and other stakeholders. The goal of requirements elicitation is to ensure that the software development process is based on a clear and comprehensive understanding of the customer's needs and requirements. To do that, exist a simple and effective tool called scenarios.

Definition 3

A **scenario** is a concrete, focused, informal description of a single feature of the system to be.

Example 5: warehouse on fire

Bob driving down main street in his patrol car notices smoke coming out of a warehouse. His partner, Alice, reports the emergency from her car.

Alice enters the address of the building, a brief description of its location (i.e. north west corner), and an emergency level. In addition to a fire unit, she requests several paramedic units on the scene given that area appears to be relatively busy. She confirms her input and waits for an acknowledgment.

John, the Dispatcher, is alerted to the emergency by a beep of his workstation. He reviews the information submitted by Alice and acknowledges the report. He allocates a fire unit and two paramedic units to the incident site and sends their estimated time of arrival (ETA) to Alice.

Alice received the acknowledgment and the ETA.

There are heuristics for finding scenarios, such as asking the customer a few questions:

- Which user groups are supported by the system to perform their work?
- What are the primary tasks that the system needs to perform?
- What data will the actor create, store, change, remove or add in the system?
- What external changes does the system need to know about?
- What changes or events will the actor of the system need to be informed about?

However, it's very important <u>not</u> to rely on questionnaires alone! Insist on task observation (if possible), ask to speak to the end user, not just the software contractor, and expect resistance, but try to overcome it.

Scenarios provide a nice summary of what the requirements analysis team can derive from observation, interviews, analysis of documentation. By generalizing the scenarios, we can get **Use Cases**.

To specify a use case, it's very important to follow the following scheme.

Definition 4: Use Cases Schema

- Name of Use Case
- Actors
 - Description of Actors involved in use case.
- Entry condition
 - "When this use case starts the following condition is true...".
- Flow of Events
 - Free form, informal natural language.
- Exit condition
 - "This use case terminates when the following condition holds...".
- Exceptions
 - Describe what happens if things go wrong.
- Special Requirements
 - Nonfunctional Requirements, Constraints.

The following **suggestions** are useful in defining an appropriate use case:

- Use cases named with verbs that indicate what the user is trying to accomplish
- Actors named with nouns
- Use cases steps in active voice
- $\bullet\,$ The causal relationship between steps should be clear
- A use case per user transaction
- Separate description of exceptions
- Keep use cases small (no more than two/three pages)
- The steps accomplished by actors and those accomplished by the system should be clearly distinguished (this helps us in identifying the boundaries of the system)

First of all, we present an example of a bad use case.

Example 6: bad use case

Example of a bad use case referring to the ambulance dispatching example on page 16:

- Use case name: Accident
- Participating Actors:
 - Field Officer
- Flow of Events:
 - 1. The Field Officer reports the accident
 - 2. An ambulance is dispatched
 - 3. The Dispatcher is notified when the ambulance arrives on site

The <u>errors</u> are as follows:

- In the *use case name* field, the **word is a noun**. It's better to use a verb that indicates what the user is trying to achieve.
- The Dispatcher actor is **not declared** in the *Participating Actors* field, but is mentioned in the *Flow of Events* field.
- There are two main errors in the *Flow of Events* section: the first is in the sentence "*An ambulance is dispatched*". But **who sends it?** The second is in the third sentence, because **who notifies the Dispatcher?**

Now we present an example of a well composed use case.

Example 7: use case ReportEmergency with reference to the example on page 21

There are two **actors** involved:

- Field Officer (Bob and Alice in the Scenario)
- Dispatcher (John in the Scenario)

The **Entry Condition** is always true because an emergency can be reported at any time. The **sequence of events** is as follows:

- The **FieldOfficer** activates the Report Emergency function of her terminal.
- **Friend** (the system to be developed) responds by presenting a form to the officer.
- The FieldOfficer fills the form, by selecting the emergency level, type, location, and brief description of the situation. The FieldOf-

ficer also describes possible responses to the emergency situation. Once the form is completed, the FieldOfficer submits the form.

- At which point, the **Dispatcher** is notified.
- The Dispatcher reviews the submitted information and allocates resources by invoking the AllocateResources use case. The Dispatcher selects a response and acknowledges the emergency report.

The **Exit Condition** is the following: the FieldOfficer has received the acknowledgment and the selected response.

There are two possible **exceptions**:

- The FieldOfficer is notified immediately if the connection between her terminal and the control room is lost.
- The Dispatcher is notified immediately if the connection between any logged in FieldOfficer and the control room is lost.

And the special requirements are:

- The FieldOfficer's report is acknowledged within 30 seconds;
- The selected response arrives no later than 30 seconds after it is sent by the Dispatcher.

Example 8: use case AllocateResources with reference to the example on page 21

- Use case name: AllocateResources
- Participating Actors:
 - Dispatcher (John in the Scenario. The Dispatcher allocates a resources to an Emergency if the resource is available; of course, he also updates and removes Emergency Incidents, Actions, and Requests in the system)
 - Resource Allocator (the Resource Allocator is responsible for allocating resources in case they are scarce)
 - Resources (the Resources that are allocated to the Emergency)
- Entry Condition:
 - An Incident has been opened
- Flow of Events:
 - The Dispatcher selects the types and number of Resources that are needed for the incident.

- Friend replies with a list of Resources that fulfill the Dispatcher's request.
- The Dispatcher selects the Resources from the list and allocates them for the incident.
- Friend automatically notifies the Resources.
- The Resources send a confirmation.

• Exit Condition:

- The use case terminates when the resource is committed.
- The selected Resource is now unavailable to any other Emergences or Resource Requests.

• Exceptions:

- If the list of Resources provided by Friend is insufficient to fulfill the needs of the emergency, the Dispatcher informs the Resource Allocator.
- The Resource Allocator analyzes the situation and selects new Resources by decommitting them from their previous work.
- Friend automatically notifies the Resources and the Dispatcher.
- The Resources send a confirmation.

4 Software Design

4.1 Software Architecture

Definition 1

The Software Architecture (SA) of a system is the set of structures needed to reason about the system. These structures comprise software elements, relations among them, and properties of both.

The software architecture is a tool for thinking about systems, and it's made up of a set of structures.

The Architecture is so important because it is the vehicle for communication: internal (different teams) and external (teams and stakeholders). The Architecture manifests the first set of design decisions and is a portable abstraction of a system.

4.2 Architecture and multiple structures

There is a set of structures relevant to the software:

- Component-and-connector (C&C) structures. Describe how the system is structured as a **set of elements** that have **runtime behavior** (called components) and interactions (called connectors).
 - The components are the principal units of computation (for example the clients, servers, services, etc.)
 - The **connectors** represent communication (for **example** request-response mechanisms, pipes, asynchronous messages, etc.)

The $\underline{purpose}$ of these structures is to enable us to answer questions such as:

- What are the major executing components and how do they interact at runtime?
- What are the major shared data stores?
- Which parts of the system are replicated?
- How does data progress through the system?
- Which parts of the system can run in parallel?
- How does the system's structure evolve during execution?

Also, allow us to study runtime properties such as availability and performance.

• Module structures. Show how a system is structured as a set of code or data units that have to be procured or constructed, together with their relations. An example of modules: packages, classes, functions, libraries, layers, database tables, etc.

Modules constitute **implementation units** that can be used as the basis for work splitting (identifying functional areas of responsibility). Typical relations among modules are: uses, is-a (generalization), is-part-of.

The $\underline{purpose}$ of these structures is to allow us to answer questions such as:

- What is the primary functional responsibility assigned to each module?
- What other software elements is a module allowed to use?
- What other software does it actually use and depend on?
- What modules are related to other modules by generalization or specialization (i.e. inheritance) relationships?

Can also be used to answer questions about the **impact on the system** when the responsibilities assigned to each module change.

• Allocation structures. Define how the elements from component-and-connector or module structures map onto things that are not software. For example hardware (possibly virtualized), file systems, teams. Some typical allocation structures include deployment structure, implementation structure, work assignment structure.

4.3 Software design descriptions and UML

In the following pages we present some diagrams that are fundamental to creating appropriate documentation. The following diagrams show how to create some UML diagrams.

4.3.1 Component Diagram (C&C structure)

A Component Diagram breaks down the actual system under development into various high levels of functionality. Each component is responsible for one clear aim within the entire system and only interacts with other essential elements on a need-to-know basis.

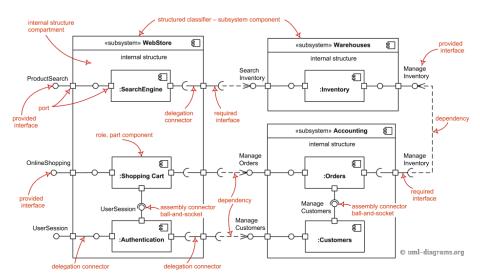


Figure 5: Component Diagram.

To view the component diagram in high resolution, scan (or click) the QR code below.



A complete guide can be found on the following page: What is Component Diagram?

4.3.2 Sequence Diagram (C&C structure)

Sequence Diagram show elements as they interact over time and they are organized according to object (horizontally) and time (vertically).

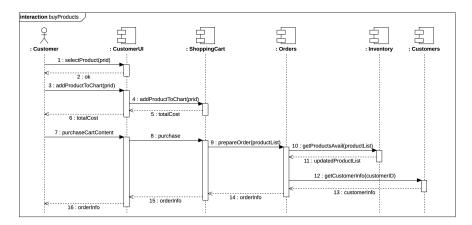


Figure 6: Sequence Diagram.

To view the sequence diagram in high resolution, scan (or click) the QR code below.



A complete guide can be found on the following page: What is Sequence Diagram?

4.3.3 Class Diagram (module structure)

A Class Diagram is a type of static structure diagram that describes the structure of a system by showing the system's classes, their attributes, operations (or methods), and the relationships among objects.

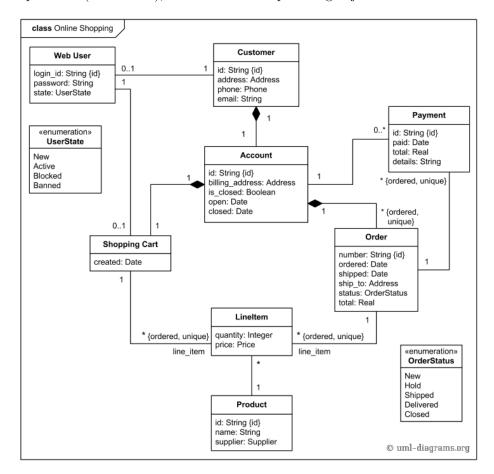


Figure 7: Class Diagram.

To view the sequence diagram in high resolution, scan (or click) the QR code below.



A complete guide can be found on the following page: What is Class Diagram?

4.3.4 Package Diagram (module structure)

A Package Diagram, a kind of structural diagram, shows the arrangement and organization of model elements in middle to large scale project. Package diagram can show both structure and dependencies between sub-systems or modules, showing different views of a system, for example, as multi-layered (aka multi-tiered) application - multi-layered application model.

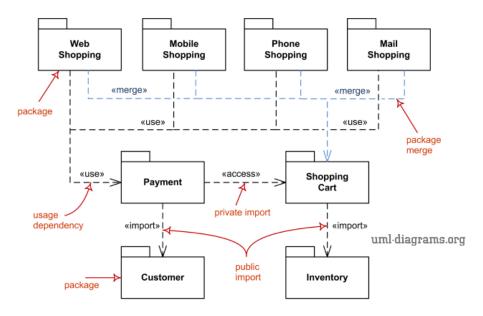


Figure 8: Package Diagram.

To view the sequence diagram in high resolution, scan (or click) the QR code below.



A complete guide can be found on the following page: What is Package Diagram?

4.3.5 Deployment Diagram (allocation structure)

A Deployment Diagram is a diagram that shows the configuration of run time processing nodes and the components that live on them. Deployment diagrams is a kind of structure diagram used in modeling the physical aspects of an object-oriented system. They are often be used to model the static deployment view of a system (topology of the hardware).

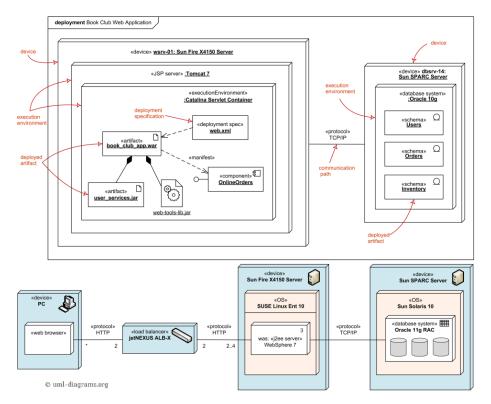


Figure 9: Deployment Diagram.

To view the sequence diagram in high resolution, scan (or click) the QR code below.



A complete guide can be found on the following page: What is Deployment Diagram?

4.4 Design principles

The following is a list of important design principles in software engineering.

Definition 2

- 1. Divide et impera (also called divide and conquer)
- 2. Keep the level of abstraction as high as possible
- 3. Increase cohesion where possible
- 4. Reduce coupling where possible
- 5. Design for reusability
- 6. Reuse existing designs and code
- 7. Design for flexibility
- 8. Anticipate obsolescence
- 9. Design for portability
- 10. Design for testability
- 11. Design defensively

1. Divide et impera (divide and conquer)

Divide and Conquer is a problem-solving strategy that involves breaking down a complex problem into smaller, more manageable parts, solving each part individually, and then combining the solutions to solve the original problem.

2. Keep the level of abstraction as high as possible

Ensure that your designs allow you to hide or defer consideration of details, thus reducing complexity. A good abstraction is said to provide *information hiding*. Abstractions allow you to understand the essence of a subsystem without having to know unnecessary details.

3. Increase cohesion where possible

In general, a file, module, class or whatever should contain the same logical methods. For example, in the following class we have two functions with two different purposes (error!).

```
Class Utility {
ComputeAverageScore(Student s[])
ReduceImage(Image i)
}
```

4. Reduce coupling where possible

Coupling is the degree of interdependence between software modules; a measure of how closely connected two routines or modules are; the strength of the relationships between modules. There are different types of couplings:

- Content coupling is said to occur when one module uses the code of another module, for instance a branch. This violates *information hiding* (2nd design principle).
- Communication coupling is said to occur when one module sends too many messages to another module. The creation of a message can be optimized and the number of messages sent between these two modules can be reduced.
- Control coupling is one module controlling the flow of another, by passing it information on what to do. For example, passing a what-to-do flag or the following code:

```
class b {
   func(flag f) {
      if(f == flag1) do this
      else if(f == flag2) do that
      else...
}
```

Other types can be viewed here.

5. Design for reusability

Design the various aspects of your system so that they can be **used again in other contexts**. To do this, you need to follow these rules:

- Generalize your design as much as possible;
- Simplify your design as much as possible;
- Follow the preceding all other design principles;
- Design your system to be extensible.

6. Reuse existing designs and code

Design with reuse is complementary to design for reusability. Take advantage of the investment you or others have made in reusable components. Note: cloning should not be seen as a form of reuse.

7. Design for flexibility

Actively anticipate changes that a design may have to undergo in the future, and prepare for them. To do this, you need to follow these rules:

- Reduce coupling and increase cohesion;
- Create abstractions:
- Use reusable code and make code reusable;
- Do not hard-code anything.

8. Anticipate obsolescence

Plan for changes in the technology or environment so the software will continue to run or can be easily changed. So do not rush using early releases of technology. If possible:

- Avoid using software libraries that are specific to particular environments;
- Avoid using undocumented features or little-used features of software libraries;
- Avoid using software or special hardware from companies that are less likely to provide long-term support;
- Use standard languages and technologies that are supported by multiple vendors.

9. Design for portability

Have the **software run on as many platforms as possible**. Avoid, if possible, the use of facilities that are specific to one particular environment (e.g. a library only available in Microsoft Windows).

10. Design for testability

Take steps to **make testing easier**. Design a program to automatically test the software:

- Ensure that all the functionality of the code can be driven by an external program, bypassing a graphical user interface;
- Create proper code to exercise the other methods/functions;
- Use unit test automation frameworks.

11. Design defensively

Be careful when you trust how others will try to use a component you are designing. Handle all cases where other code might attempt to use your component inappropriately. Check that all of the inputs to your component are valid: the preconditions. Unfortunately, over-zealous defensive design can result in unnecessarily repetitive checking.

5 Architectural styles

5.1 Definition

Definition 1

An architectural style determines the **vocabulary** of **components** and **connectors** that can be used in instances of that style, together with a set of **constraints** on how they can be combined.

These can include topological constraints on architectural descriptions (e.g., no cycles). Other constraints - say, having to do with execution semantics - might also be part of the style definition.

5.2 Client-Server

A Client-Server Architecture is a network-based computing structure where responsibilities and operations get distributed between clients and servers. Client-Server Architecture is widely used for network applications such as email, web, online banking, e-commerce, etc.

✓ When to use it

The three most common cases are:

- When multiple users need to access a single resource (e.g. database).
- When there is a preexisting software and we must **access remotely** (e.g. email server).
- When it is convenient to organize the system around a shared piece of functionality used by multiple components (e.g. authentication or authorization server).

▲ Technical issues

With this architecture, it's necessary to **design** and **document** proper **interfaces** for our server. It is also necessary to ensure that the server can **handle multiple simultaneous requests**.

5.2.1 Interface design

An **interface design** is a **boundary** across which components interact. Proper definition of interfaces is an architectural concern (affects maintainability, usability, testability, performance, integrability). There are two important **guiding principles** for interface design: **information hiding** and **low coupling**. An interface should encapsulate a component implementation so that it can be changed without affecting other components.

There are several aspects to interface design that need to be considered:

- Contract principle: any resource (operation, data) added to an interface implies a commitment to maintaining it.
- Least surprise principle: interfaces should behave consistently with expectations.
- Small interfaces principle: interfaces should limit the exposed resources to the minimum.

There are also some important elements to define: **interaction style** (e.g. sockets, RPC, REST); **representation** and structure of exchanged data (affecting expressiveness, interoperability, performance and transparency); **error handling**.

5.2.2 Error handling, multiple interfaces and interface evolution

Sometimes there may be some problems, for example: an operation is called with invalid parameters and consequently the call doesn't return anything. This simple example can provoke some scenarios: the component cannot handle the request in its current state; or hardware/software errors prevent successful execution; or there is a misconfiguration issue (e.g. the server is not correctly connected to the database).

There are three possible solutions: raising an exception; return an error code (common); log the problem. There's no single solution, but we can choose several (e.g. error code and log the problem).

A server can offer multiple interfaces at the same time. This enables separation of concerns, different levels of access rights and support of interface evolution.

Interface evolution occurs for many reasons (e.g. to support new requirements). Several **strategies** are needed to support continuity:

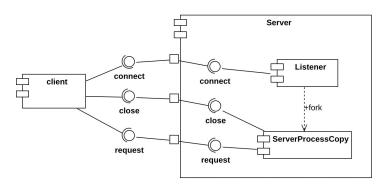
- **Deprecation**: declare well in advance that an interface version will be retired by a certain date;
- Versioning: maintain multiple active versions of the interface;
- Extension: a new version extends the previous one.

5.2.3 Handling multiple requests

The server must be able to receive and process requests from multiple clients. There are two main approaches to this: forking and worker pooling.

Forking

The **forking** approach is the same as that used by the Apache Web Server: **one process per request or per client**.



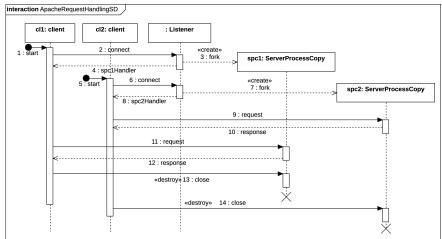


Figure 10: Forking diagrams.

✓ Forking Advantages

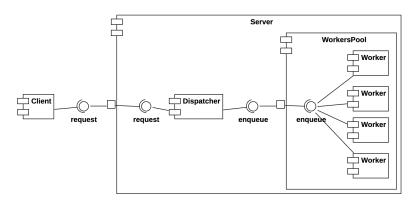
- Architectural **simplicity**.
- **Isolation** and **protection** given by the one-connection-per-process model. Note: slow processes do not affect other incoming connections.
- Simple to program.

▲ Forking Issues

- Growth of the WWW over the last 20 years (number of users and weight of web pages).
- ullet The number of active processes at time t is difficult to predict and may saturate resources.
- Expensive fork-kill operations for each incoming connection.

Worker pooling

It is an alternative approach adopted by NGINX Web Server. It is **designed** for high concurrency but has to deal with scalability issues.



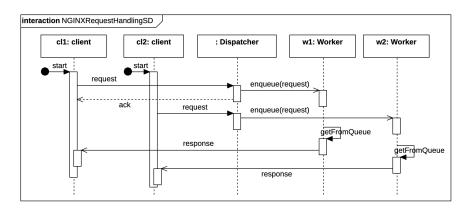


Figure 11: Worker pooling diagrams.

Despite the well-known problem of this architecture (scalability), NGINX addresses the previous problems by introducing a new **architectural tactic**. A *tactic* is a **design decision that affects the control of one or more quality attributes**.

✓ Worker Pooling Advantages (quality attribute trade-offs)

- Number of workers is fixed, so they do not saturate available resources.
- Each worker has a queue.
- When queues are full the dispatcher drops the incoming requests to keep high performance (optimize scalability and performance by sacrificing availability).
- Dispatcher balances the workload among available workers according to specific policies.

5.3 Three-Tier Architecture

The following is a summary of the IBM guide.

Three-tier architecture is a well-established software application architecture that organizes applications into three logical and physical computing tiers:

- The **presentation** tier, or user interface;
- The application tier, where data is processed;
- The data tier, where application data is stored and managed.

✓ Benefits

The chief benefit of three-tier architecture is its **logical and physical sepa- ration** of functionality. Each tier can run on a separate operating system and
server platform - for example, web server, application server, database server that best fits its functional requirements. And each tier runs on at least one
dedicated server hardware or virtual server, so the services of **each tier can be customized and optimized without impacting the other tiers**. Other
benefits include:

- Faster development: Because each tier can be developed simultaneously by different teams, an organization can bring the application to market faster. And programmers can use the latest and best languages and tools for each tier.
- Improved scalability: Any tier can be scaled independently of the others as needed.
- Improved reliability: An outage in one tier is less likely to impact the availability or performance of the other tiers.
- Improved security: Because the *presentation tier and data tier can't communicate directly*, a well-designed application tier can function as an internal firewall, preventing SQL injections and other malicious exploits.

5.3.1 N-tier architecture

N-tier architecture (also called or multitier architecture) refers to any application architecture with more than one tier. But applications with more than three layers are <u>rare</u> because extra layers offer few benefits and can make the application slower, harder to manage and more expensive to run. As a result, n-tier architecture and multitier architecture are usually synonyms for three-tier architecture.

5.4 Microservice architectural style

The microservice architectural style is an approach to developing a single application as a suite of **small services**, each running in its own process and communicating **lightweight mechanisms**, often an HTTP resource API.

✓ Benefits

There are two main benefits:

- Technology heterogeneity. Each service uses its own technology stack. The technology stack can be selected to fit the task best (e.g. data analysis vs video streaming). The teams can experiment with new technologies within a single microservice (e.g. we can deploy two versions and do A/B testing). Also, no unnecessary dependencies or libraries for each service.
- Scaling. Each microservice can be scaled independently. Also, identified bottlenecks can be addressed directly. Parts of the system that do not represent bottlenecks can remain simple and unscaled.

References

[1] F. Bomarius, M. Oivo, P. Jaring, and P. Abrahamsson. *Product-Focused Software Process Improvement: 10th International Conference, PROFES 2009, Oulu, Finland, June 15-17, 2009, Proceedings.* Lecture Notes in Business Information Processing. Springer Berlin Heidelberg, 2009.

Index

A Allocation	27
\mathbf{C}	
Class Diagram	30
Client-Server Architecture	37
Coding and Unit Test	8
Communication coupling	34
Component Diagram Component-and-connector (C&C)	28 27
Compute-intensive applications	11, 12
Constraints requirements	19
Content coupling	34
Contract principle	37
Control coupling	34
Correctness	12
Coupling	34
D	
Data-intensive applications	11, 13
defect	13
Deployment	9
Deployment Diagram Design	32 8
Divide and Conquer	33
Domain properties	17
E	19
Evolvability	13
\mathbf{F}	
fault	13
fault-tolerant	13
Feasibility Study	8
forking Functional requirements	39 19
runctional requirements	13
G	
Goals	17
H	
Hardware Faults	14
I	_
Integration and System Test	8
interface design	37
${f L}$	
Least surprise principle	37

M machine Maintainability Maintenance Module multiple interfaces	16 12, 13 9 27 38
N N-tier architecture Non-functional requirements (NFRs)	42 19
O Operability	12
P Package Diagram Parallel and Distributed Computing (PDC) Performance Portability	31 10 12 12
Reliability Requirement Engineering Requirements Requirements Analysis and Specification Requirements Elicitation resilient	13 15 17 8 21 13
S Scalability scenario Sequence Diagram Simplicity Small interfaces principle Software Architecture (SA) Software Faults system failure	13 21 29 12 37 26 14
T Three-tier architecture	42
U Use Cases	22
W waterfall model world	8 16