Software Engineering for HPC - Notes

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Preface

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

None

About:

GitHub repository

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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

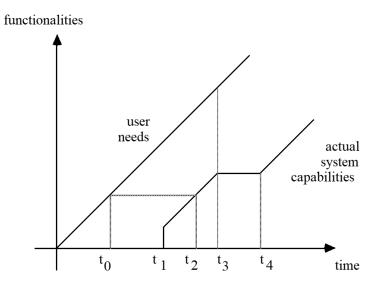
1.3.2 Productivity

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

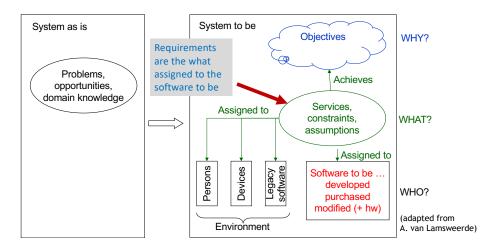


Figure 2: Analyzing the system as is and the system to be.

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.

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.

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