

Formal Software Engineering (génie logiciel avec l'approche formelle)

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Two parts course, given with Pr. Claude Jard

About me: Teaching at IUT & UFR Sciences - Research at LINA

Dpt Info IUT

- Modélisation de données
- Modélisation de la dynamique
- Méthode B

Dpt Info UFR Sciences

- Formal Software Engineering (*Construction formelle de logiciels*)

LINA - UMR 6241 / Université de Nantes - CNRS - Mines de Nantes

- Topic **ALD**: AeLoS, Ascola, GDD, GRIMM
- Topic **SAD**: COD, COMBI, Contraintes/TASC, OPTI, TALN

Research Topics

- Construction of Correct Architecture and Software
- Modelling, Verification, Refinement, Semantics
- Distributed Systems (services, components, architecture, properties)

AeLoS Team Members

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Introduction

- Computer Systems (*Systèmes informatiques*)?
- Construction?
- What issues?
- **What concepts, theories, methods, techniques, tools?**
- State of the art?
- The needs?

Introduction

Nowadays, computers and softwares are everywhere

- Domestic devices, home automation, leisures
- Medical domains
- Transportation (airplanes, trains, cars, ...)
- Administration (integrated databases + decision systems)
- Various services (booking, health control, home control,)
- Bank and Financial systems
- Politics, electronic votes, analysis
- etc

What about the quality of software with respect to its critical place?

Do we know how to build it well?

Do we know how to maintain it well?

With **What methods, techniques, tools?**

Introduction: Industry adopts FM

Difficulties for industries: Market Pressure, High costs, ...

BUT, there are numerous success stories

- Proof of a compiler (Coq, Xavier Leroy, 2011)
- Design of a Real-Time Operating System (TLA+)
 - E. Verhulst, R.T. Boute, J.M. Sampaio Faria, B.H.C Spath, V. Mezhuyev, Formal Development of a Network-Centric RTOS, 2011
- Proof of IEEE 1395 Firewire Protocols (Spin, PVS, B, +++ ; 2004+)
- Proof of control systems (B, Siemens)
- Proof of circuit (STMicroelectronics)
- BOS barrier protecting the harbor of Rotterdam (Z, 2001)
- Proof of microcode and software (Intel)
- Proof of Communication Protocols (IO Automata, 1993+)

The complexity of current computer systems discourages empirical methods.

Introduction : Proof the correction of a software

Proof the correction of a software S

- The model of the software : M
- The properties : P
- $M \models P$ or prove that P is true in all the (reachable) states of M

☞ Learn how to build M , P and how to prove (using dedicated tools or not).

Presentation of this Course (48h)

Formal modelling and verification of software

(the only way amenable to prove software correctness)

- Part 1 - by Claude Jard (~ 24 hours)
[Concurrency and Semantic Models](#) ;
 Petri Nets/Romeo (model checking).
- Part 2 - by Christian Attiogbé (~ 24 hours)
[Correct Construction with B Method, Event-B](#)
 Atelier B/Rodin (theorem proving).

Agenda

- First lesson, this one, Christian Attiogbé
- Part1: Six lessons + assessment, by Prof. Claude Jard followed by
- Part2: Five lessons + assessment, by Prof. Christian Attiogbé

Example of formal models or specifications

```

MACHINE /* Sorting: a set of naturals -> seq. of natural */
  Tri
CONSTANTS
  tride /* defining a function */
PROPERTIES
  tride : FIN(NAT) --> seq(NAT) &
  (ran(tride(ss)) = ss &
   jj : dom(tride(ss)) &
   ii < jj =>
    (tride(ss))(ii) < (tride(ss))(jj) ) ) )
END

```

Emphasize **abstraction** = what (not how)

Example of formal specifications

```

system ProdCons /* Model */
sets
  DATA ;
  STATE = {empty, full}
variables
  buffer, bufferstate, bufferc
invariant
  bufferstate ∈ STATE
  ∧ buffer ∈ DATA ∧ bufferc ∈ DATA
initialization
  bufferstate := empty
  || buffer :∈ DATA
  || bufferc :∈ DATA
end

```

Emphasize **abstraction**

Example of formal specifications

ProdCons (continued)...

```

events
  produce  $\hat{=}$  /* when buffer empty */
    any dd where
      dd  $\in$  DATA  $\wedge$  bufferstate = empty
    then
      buffer := dd ||
      bufferstate := full
    end ;
  consume  $\hat{=}$  /* when buffer is full */
    select bufferstate = full
    then
      bufferc := buffer ||
      bufferstate := empty
    end
end

```

Emphasize abstraction = what (not how)

Example of properties

Always an unique process in CS	$card(activeProc) = 1$
A process cannot be simultaneously active and blocked	$activeProc \cap clockedProc = \emptyset$
...	...

👉 The use of invariant properties

- **Safety properties:** *nothing bad should happen*
 - **Liveness properties:** *something good eventually happens*
- More generally, one uses Modal Logics.

Motivations

MASTER level \Rightarrow Managing industrial projects
(computer systems) in various domains, variable size (small or big)
Complex CS projects \Rightarrow **Methods, Techniques, Tools**

- **Analysis** Methods,
- **Design & Verification** Methods,
- **Development/Implementation** Methods.

Motivations (continued)

Examples of semi-formal methods

- Functional Analysis (SA..., SADT),
- Structured Analysis (SA, SSADM), SA-RT,
- Entity-Relationship (*Entités/Associations*): Merise, Axiale,
- JSD/JSP,
- Object-Oriented Analysis, OMT, UML,
- Software Architecture (System Level ; Top-Down approach),
- etc

Motivations (continued)

Need of rigorous methods for some specific domains:

- Security, Certification, Cost, Maintenance
- ITSEC (Information Technology Security Evaluation Criteria) requires the use of **formal methods**
- Failure of (one flight) of ARIANE!, failure of a Pentium series, etc
- Environments which are dangerous for humans (nuclear, chemistry, marine, etc)
- Embedded Systems (vehicles, home equipments, etc)
- Automata (medical domain, etc)
- etc

Examples

Examples of formal methods

- Logics (First Order, Higher Order, Modal)
- Finite State Machines (Mealy, Moore, ...)
- Transition systems (Automata, Petri nets, Communicating processes,...)
- Algebraic Methods
- Timed Systems (extension of Transition systems)
- ...

Features of Formal Methods

Formal methods \Rightarrow use rigorous approach to

- guaranty of **software correction** with respect to specifications,
- **decrease/remove errors**, and disfunctioning,
- **make it easy the maintenance and the evolution.**

Introduction to Formal Methods

Construction methods of computer systems

A few analogies:

Building Engineering (*Génie civil*)

→ Architecture, schemes/blueprints (design), computings, construction (implementation)

Physics

→ Observations, modelling/study of models, implementation

Computer Science (Informatique)

\Rightarrow

Requirement Analysis (observations?)

Modelling - study of models,

Design and Implementation of systems.

Preliminaries

Various approaches of formal methods:

- **à postériori** : First, one implements (programming paradigm) and then one verifies that the produced program is correct
→ proof systems, testing, model-checking
- **à priori** : **One builds correctly the system**
→ Development methods (refinement, synthesis), proof systems

Several formal methods (languages, proof systems, methods)

Preliminaries

- **Top-down** approach: by **decomposition**
 - Global analysis (system study, system engineering)
 - Software Architecture
 - ↓
 - Implementation of components
 - Direct Programming or
 - Formal Development
- **Bottom-up** approach: **composition** of elementary components.
 - Study of available components,
 - Composition, reuse.

Need of formal methods

In all cases (approaches), make use of formal methods for

- Study of systems
- Study and construction of components
- Formal framework for reasoning, analysis, development.

What are inside formal methods?

- Logics
- Algebra
- Discrete Mathematics
- Set Theory
- Automata Theory
- Type Theory
- Refinement Theory
- ...

Examples of a few industrial applications

with Z , VDM , CSP

- IBM, INMOS, ...
- CICS: IBM interactive transactional system (1983, Z)
- Integrated Circuit Design, Transputer (Z , CSP)
- etc

Examples of a few industrial applications

with the **B Method** (J-R. Abrial)

GEC ALSTHOM, SNCF and MATRA Transport (now Siemens)

- Railway Speed Control System (KVS for SNCF)
- Line A of the Paris RER - SACEM (signaling, speed control)
- Calcutta Metro (CTDC)
- Montreal Metro(CTDC), Marseille, Bel horizonte
- Météor (line 14, of Paris Metro, without human driver)
- Landing doors (*portes palières*) in Metro stations
- Old people insurance, in French Sécurité Sociale
- CICS of IBM (major restructuring of a transactional, about 800000 lines of code)
- B and VDM are used in financial domain softwares, BULL UK

Many other systems with Petri Nets, Lotos, etc

Example of the Railway Speed Control System (Metro)

- Data acquisition (sensors, converters, etc),
- Computation/decision,
- Orders sent to physical devices (speed slowing system, braking system),
- Embedding of the software in the global system of the train.

Other used approaches

Some of them are equipped with tools and adopted by industries

RAISE (Result of an european project - ESPRIT)

algebraic approach + *communicating processes*

LOTOS, SDL (Standard européen)

algebraic approach + *communicating processes*

PVS (USA)

MEC, AltaRica (Université de Bordeaux + industries)

Classical Logics: First order Logic, Hoare Logic, etc

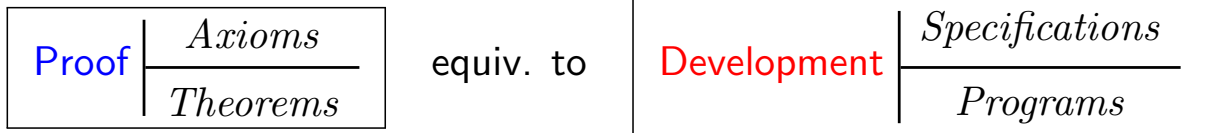
(Why, Frama-C, Krakatoa (Java), Key,...)

Non-classical Logics, modal logics

Coq, High-Order Logics, type theory

Foundation of formal approaches (proof)

Interpretation of the **Curry-Howard's Isomorphism**:



Approach of Formal Construction

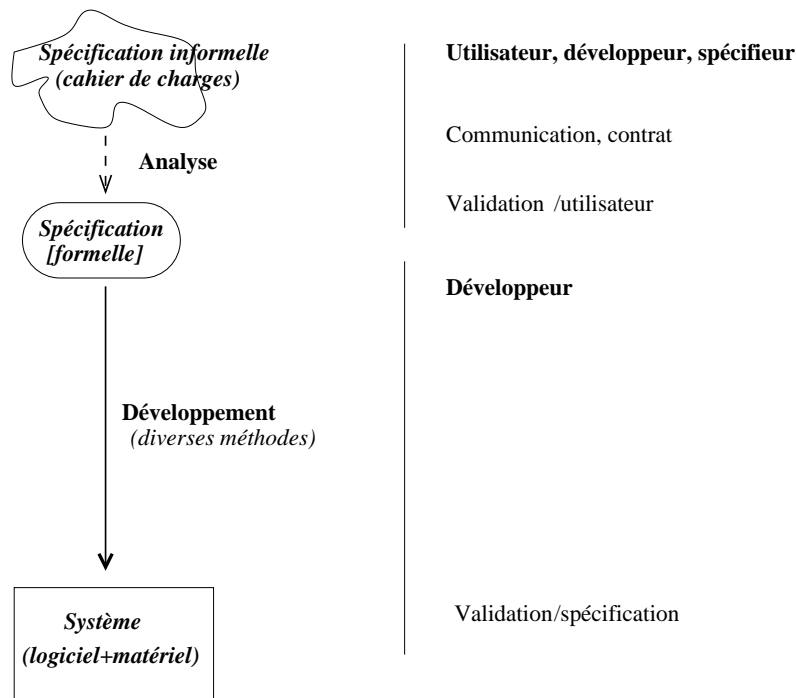


Figure: Issue of system development de system

Overview of Software Construction

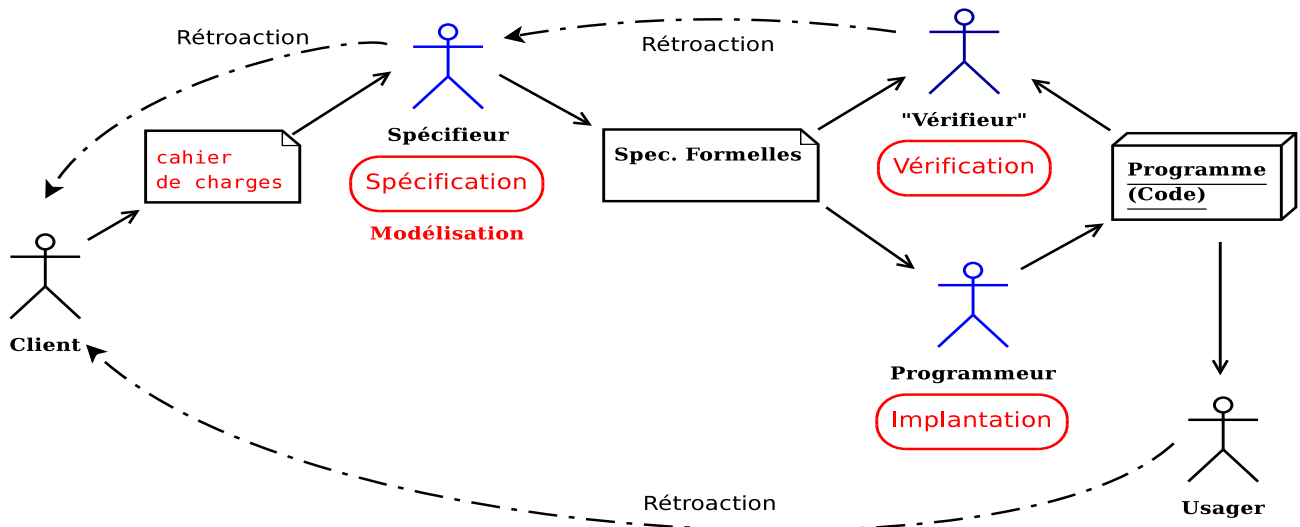


Figure: A life cycle of formal software construction

Use of Formal Methods

- **Not always appropriate:**
- A hammer to kill a fly
 - depending on the needs
 - Professional environment
 - Available experiments?
 - Industrial context
 - Delay, costs, productivity
 - Certification
 - Requirements of clients.

Which approach to use?

→ Several parameters:

- Designer/implementor of big systems,
- Designer/implementor of small (home) systems,
- **Features** of systems to be implemented,
- Available experiments,
- ...

Categories of Software Systems

Nature	Features?	Methods?
sequential		
autonomous (transformational)		
centralised		
reactive		
real-time		
parallel		
parallel and concurrent		
distributed		
embedded		
communication protocols		
...		

⇒ various types of software systems, various methods

A few difficult points

- To describe precisely the intended system **specification**
- To build correctly the software **development**
- To be sure that the constructed software is **correct with respect to the needs**
- Maintenance/Evolution of the system.

Example of the B Method

The built system is correct by construction : stepwise refinement from abstract model

- **Initially** (< 1996), sequential execution semantics, for sequential systems; no behavioural indeterminism
- **Then**, extended (Event-B, 1998) for autonomous and reactive systems, concurrent and distributed systems.

Example of LOTOS

Analysis and verification of systems (already developed or not)

- Sequential and concurrent execution models
Concurrent and sequential systems
- Possibility of behavioural indeterminism
- Autonomous and reactive systems
- Centralised and distributed systems.

Steps of the software life cycle

From requirement document → computer system
requirement document = informal specification

Several steps:

- Analysis
- Specification, Modelling
- Design
- Implementation
- Maintenance

Practice

Each project is unique

- Nature of complex systems → **multifacets**, modular
- Several methods, including:
 - Semi-formal methods
 - Formal Methods (integrated) → to deal with complex systems.

⇒ **mastering several methods**

A few definitions

Modelling:

Hoare: A scientific theory is formalised as a mathematical model of reality, from which can be deduced or calculated the observable properties and of a well-defined class of processes in the physical world.

There are two main notions of models in computer science.

- ① **Model = an approximation of the reality by a mathematical structure.**
An object O is a model of a reality R , if O allows one to answer all the questions about R .

In Mathematics, Physics, ... models are built with equation systems using quantities (masses, energy, ...) or hypothetic laws.

A few definitions (continued)

2 Logics, theory of models

A model of a theory T is a structure in which the axioms of T are valid.

A *structure* S is a model of a theory T , or S satisfies T if all formula of T is satisfied in S .

The reality is a model of a theory!

First Order Theory = any set of logic formula in a given language (precisely defined).

Model as an interpretation of a specification - an algebra as a model of an algebraic specification (or an axiomatisation).

A few definitions (continued)

These two notions of *model* are encountered in the **model-oriented (or state-oriented)** and **property-oriented** approaches of Soft. Eng.

In current use,

- *model* = (archetype), what serves or is used for imitation to reproduce other instances.
- *model* = (paradigm), declination model, conjugation model, etc
- *model* = (reference), ...

Examples of theory

Set theory: it is based on a set of axioms (Bourbaki, Cantor, Zermelo, ...).

The objects of this theory are called **sets**.

The classe of the sets is called the **universe**.

The axioms of the set theory (of Zermelo+Fraenkel) are the following:

Examples of theory (continued)

- **Axiom of the empty set:** *there exists a set which does not contain any element: it is the empty set.*
- **Extensionality Axiom:** *two sets are equal if and only if they contain exactly the same elements.*
- **Union Axiom:** *the union of sets is a set.*
- **Axiom of the set of parts:** *given a set E , there exists a set P such that a set F is member of P if F is a part of E .*
- **Axiom of replacing/substitution schema (Fraenkel, 1922) :** *When one defines a function with the formula of the set theory, the elements for which this function verifies a given property are also a set.*

Moreover, to these axioms is added, the **axiom of infinite:** *there exists an infinite ordinal.*

ZFC = ZF + axiom of choice

- **Axiom of choice:** *Given a family of disjoint sets, if we consider one element of each set of the family, then one builds another set.*

A few definitions (continued)

Semiformal Method =

- Graphical Language [+ formal]
(precise syntax and unprecise semantics) and
- Various analysis tools.

→ Combination of languages/methods/techniques that do not all have a precise semantics.

Examples : JSD, OMT, OOX, UML

Interest and Limitations of Semi-formal Methods

- SADT, SA-RT, SSADM, ...
- JSD-JSP,
- Merise, Axial, ...
- OOA, OMT, UML
- ...

The problem analysis is performed.

It is a positive contribution, although insufficient.

The problem is sided.

→ impossible to reason formally on the intended system.

→ there can be ambiguities and errors.

A few definitions (continued)

Formal Method =

- Formal Language (precise syntax and precise semantics) and
- Proof or formal reasoning system.

Examples: FSM, RdP, Z, CCS, CSP, HOL, Coq, PVS, B, ISabelle
Formal Development =

- **systematic transformation of specifications into programs** using predefined laws/rules. **Examples: Synthesis, Refinement**

Examples: B Method, Perfect, Escher C, Coq

A few definitions (continued)

Verification: to show that a system (S) is correct with respect to some properties (P)

$$S \models P$$

Validation: to show that a system (S) is correct with respect to some informal properties (the needs)

$$S \sim S_{informal}$$

Formal reasoning : Consists in **applying a formal system to a specification.**

Examples of formal reasoning

- Refinement of specification,
- Verification of the properties of a system,
- Validation via verification,
- Proof of theorems (*theorem proving*),
- Analysis of a system (represented by a state machine) wrt some properties (*model checking*).

⇒ Logic is the foundation of the formal approaches

Software Life Cycles

- Life cycles have been for longtime, the methodological support of software development.
- the most representative life cycles are:
 - the V software life cycle,
 - the Cascade life cycle or 'Iterative Waterfall' life cycle,
 - Balzer's cycle, 1980+
 - Spiral life cycle by Barry Boehm, 1986

Software Life Cycle

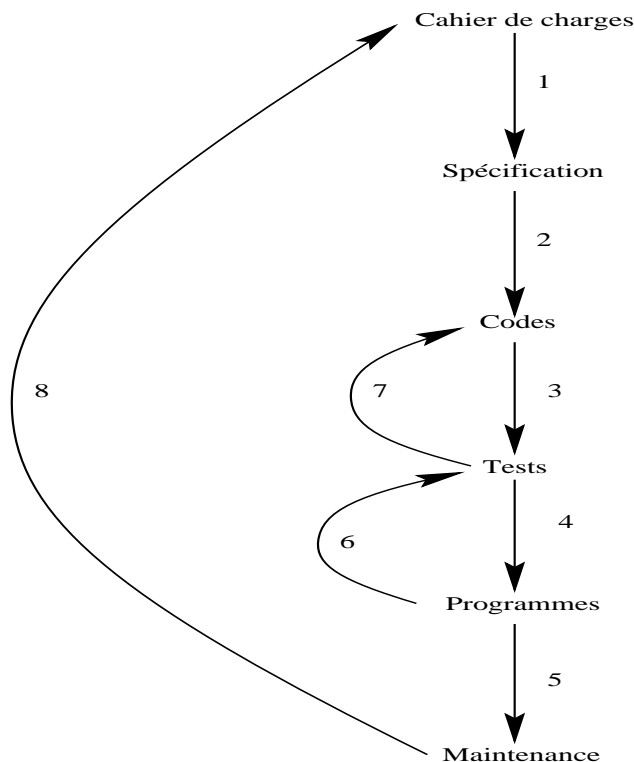


Figure: Cascade life cycle (by Boehm, 1977)

Formal Specification

⇒ Description in a formal language of the 'What is' a system to be developed.

- Result of the analysis step.
- Several possible forms depending on the nature of the system.

One considers **languages** or **formalisms** of formal specification:

Logics, Z, Algebraic Specification Languages, process algebra, etc

Specification Approaches

Data or operations aspects first?

- The data of a system permit to describe the state of the system
- The operations of a system enable to describe its behaviour with axioms.

There are the **data paradigm** and the **operation paradigm**.

One should distinguish the operations expressing the behaviour of a system from the operations that characterise the data of the system.

The former work on the data of the system whereas the later are used to build or or manipulate the system data.

Specification Approaches

There are a third transversal paradigm.

It is the **process paradigm** (with the **process algebra**).

With this paradigm, the processes of a system are described with rules or equations that express the system behaviour or its states.

The main process algebra used to build others are:

- CSP (Hoare)
- CCS (Milner)
- ACP (Bergstra)

They are all based on the Transition System Approach.

Specification Approaches

You have to choose the one which is appropriate to a given problem!

Learn the main ones! and be able to move to others.

The remaining of the course has this objective.

Examples - Case studies

Preliminary examples and case studies

- Requirement analysis
- Abstraction
- Modelling
- ...

A few references

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