LIX, École Polytechnique

Software Modelling and Architecture: Exercises

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Chapter 1

Introduction

This exercise book is meant to go with the course INF561 given at École Polytechnique by Prof. D. Krob. The current course edition is 1st semester 2007/2008. It contains a series of exercises in software modelling and architecture.

1.1 Structure of this book

Software modelling and software architecture are concepts needed when planning complex software systems. The book will focus on exercises to be carried out by means of the UML language, some notions of optimization, and a good deal of common sense. One becomes a good software architect by experience.

Chapter 2 focuses on simple UML exercises. It is split in Sections 2.1 (use case diagrams), 2.2 (sequence diagrams) and 2.3 (class diagrams). Chapter 3 groups various modelling exercises, only some of which involve UML. Chapters 5 and 6 are large scale exercises that should give meaningful examples on various modelling techniques in practice (these sometimes employ UML-like diagrams, but are not based on UML). Since some of the large scale exercises use mathematical programming techniques, there is a small collection of exercises on mathematical programming in Chapter 4.

Chapter 2

UML exercises

This chapter proposes small to medium scale exercises on UML. Some of them are by the author, whilst others have been taken from books (credits are made explicit in each exercise: where no explicit citation is given, the exercise is to be considered the author's work).

2.1 Use case diagrams

In this section we give some examples of use case diagrams for various situations.

2.1.1 Simplified ATM machine

Propose a use case diagram for an ATM machine for withdrawing cash. Make the use case simple yet informative; only include the major features.

2.1.2 Vending machine

Propose a use case diagram for a vending machine that sells beverages and snacks. Make use of inclusion and extension associations, mark multiplicities and remember that a vending machine may need technical assistance from time to time.

2.2 Sequence diagrams

In this section we shall present some easy examples of sequence diagrams.

2.2.1 The norm of a vector

Consider the following algorithm for computing the norm of a vector.

```
Class Array {
  ...
```

```
  public:

    // return the index-th component of the array
    double get(int index);
  ...
};

double norm(const Array& myArray) {
  double theNorm = 0;
  for(int index = 0; index < myArray.size() - 1; index++) {
    theNorm = theNorm + myArray.get(index);
  }
  theNorm = sqrt(theNorm);
  return theNorm;
}
```

Write down a sequence diagram that describes the `norm()` function.

2.2.2 Displaying graphical objects

Write a sequence diagram for a program that displays Fig. 2.1 on the screen in the order left → right.

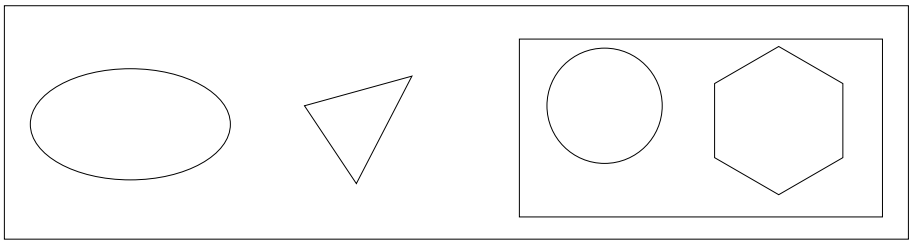


Figure 2.1: The sequence diagram describing the computation of the norm of a vector.

2.2.3 Vending machine

Draw a sequence diagram for the vending machine of Sect. 2.1.2.

2.3 Class diagrams

In this section we present some elementary exercises on class diagrams.

2.3.1 Complex number class

Draw a class diagram for the single class `Complex`. A `Complex` object has a private real and an imaginary part (of type `double`), and can perform addition, subtraction, multiplication and division by another complex number.

2.3.2 Singly linked list

Draw a class diagram representing a singly linked list.

2.3.3 Doubly linked list

Draw a class diagram representing a doubly linked list.

2.3.4 Binary tree

Draw a class diagram representing a binary tree.

2.3.5 n-ary tree

Draw a class diagram representing an n-ary tree (a tree with a variable number of children nodes).

2.3.6 Vending machine

Draw a class diagram for the vending machine described in Sect. 2.1.2 and 2.2.3.

Chapter 3

Modelling

This chapter groups some modelling exercises, only some of which involve UML.

3.1 The vending machine revisited

Consider the vending machine described in Sect. 2.1.2, 2.2.3 and 2.3.6. The proposed use case diagram (Fig. **??**), sequence diagram (Fig. **??**) and class diagram (Fig. **??**) make up for a very poor system modelling indeed. The vending machine is always thought of as a monolitic entity: this makes the external relationships clear but says nothing about how to plan and build one. In particular, the monolitic view is incompatible with the fact that a vending machine is composed of different parts. Given the following list of parts:

1. main controller
2. mechanical robot
3. coin acceptor
4. remote messaging system
5. door

and the fact that 2,3,4,5 can only be interfaced with 1, draw a use case diagram and a sequence diagram to provide an initial blueprint for the inner workings of a vending machine.

3.2 Mistakes in modelling a tree

Fig. 3.1 describes the class diagram of a tree node, which can be used recursively to build an expression tree.

Generate the header file and implementation code using Umbrello, then add the implementation of the only non-obvious functions (`getNumberOfChildren` and `getChildType`) as follows:

```
int TreeNode::getNumberOfChildren ( ) {
  // number of children
  int nc = 0;
```

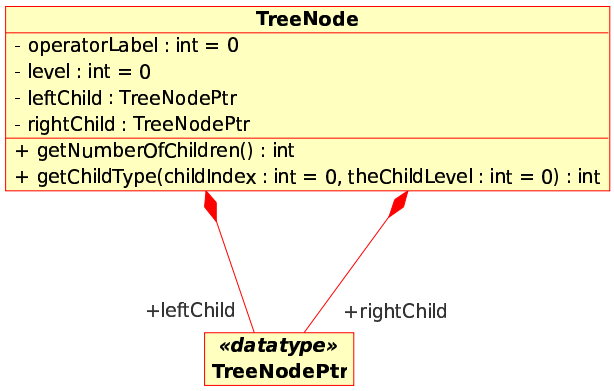


Figure 3.1: The UML class diagram for the `TreeNode` class.

```
  switch(m_operatorLabel) {
  case 0: // sum
    nc = 2;
    break;
  case 1: // difference
    nc = 2;
    break;
  case 2: // multiplication
    nc = 2;
    break;
  case 3: // division
    nc = 2;
    break;
  case 4: // square
    nc = 1;
    break;
  case 5: // cube
    nc = 1;
    break;
  case 6: // sqrt
    nc = 1;
    break;
  case 10: // number
    nc = 0;
    break;
  default:
    break;
  }
  return nc;
}

int TreeNode::getChildType (int childIndex, int theChildLevel) {
  int ret = -1;
  // increase the level by one unit
  theChildLevel++;
  if (childIndex == 0) {
    // left child
    ret = m_leftChild->getOperatorLabel();
  } else if (childIndex == 1) {
    // right child
    ret = m_rightChild->getOperatorLabel();
```

```
    }
    return ret;
  }
```

Now consider the following `main` function in the file `TreeNode_main.cxx`:

```
// TreeNode_main.cxx

#include <iostream>
#include "TreeNode.h"

int main(int argc, char** argv) {

  int ret = 0;

  // expression tree t: number + number^2
  TreeNode t;
  t.setOperatorLabel(0);
  t.setLevel(0);
  t.setLeftChild(new TreeNode);
  t.setRightChild(new TreeNode);
  t.getLeftChild()->setOperatorLabel(10);
  t.getLeftChild()->setLevel(1);
  t.getRightChild()->setOperatorLabel(4);
  t.getRightChild()->setLevel(1);
  t.getRightChild()->setLeftChild(new TreeNode);
  t.getRightChild()->getLeftChild()->setOperatorLabel(10);
  t.getRightChild()->getLeftChild()->setLevel(2);

  // get right child type and level
  int theLevel = 0;
  int theOperatorLabel = -1;
  theOperatorLabel = t.getChildType(1, theLevel);

  // expect theOperatorLabel = 4, theLevel = 1;
  std::cout << theOperatorLabel << ", " << theLevel << std::endl;
  // actual output is 4,0

  return ret;
}
```

Compile the project by typing:

```
c++ -o TreeNode TreeNode_main.cxx TreeNode.cpp
```

and verify whether the output is as expected (`4, 1`). If not, why? Is this a bug or a modelling error?

We would now like to code in `TreeNode_main.cxx` a new function that accepts a tree node and returns the number of children of the root node of the expression tree. Convince yourself that you cannot do this easily, and explain why. How can you fix this modelling error? Change the UML diagram and the code accordingly.

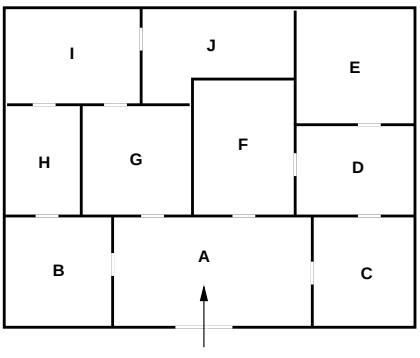
Chapter 4

Mathematical programming exercises

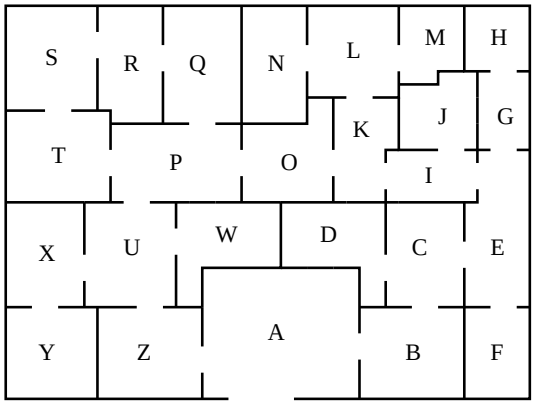
The mathematical programming formulation language is a very powerful tool used to formalize optimization problems by means of parameters, decision variables, objective functions and constraints. Such diverse settings as combinatorial, integer, continuous, linear and nonlinear optimization problems can be defined precisely by their corresponding mathematical programming formulations. Its power is not limited to its expressiveness, but usually allows hassle-free solution of the problem: most general-purpose solution algorithms solve optimization problems cast in their mathematical programming formulation, and the corresponding implementations can usually be hooked into language environments which allow the user to input and solve complex optimization problems easily. This chapter provides an introduction (by way of examples) to a mathematical programming software system, called AMPL (A Mathematical Programming Language) [2] which is interfaced with continuous mixed-integer linear (CPLEX [4]) and nonlinear solvers. See `www.ampl.com` for details on downloading and installing the student versions of AMPL and CPLEX.

4.1 Museum guards

A museum director must decide how many guards should be employed to control a new wing. Budget cuts have forced him to station guards at each door, guarding two rooms at once. Formulate a mathematical program to minimize the number of guards. Solve the problem on the map below using AMPL.



Also solve the problem on the following map.



[*P. Belotti, Carnegie Mellon University*]

4.2 Mixed production

A firm is planning the production of 3 products A_1,A_2,A_3. In a month production can be active for 22 days. In the following tables are given: maximum demands (units=100kg), price (\$/100Kg), production costs (per 100Kg of product), and production quotas (maximum amount of 100kg units of product that would be produced in a day if all production lines were dedicated to the product).

Product	A_1	A_2	A_3
Maximum demand	5300	4500	5400
Selling price	\$124	\$109	\$115
Production cost	\$73.30	\$52.90	\$65.40
Production quota	500	450	550

1. Formulate an AMPL model to determine the production plan to maximize the total income.
2. Change the mathematical program and the AMPL model to cater for a fixed activation cost on the production line, as follows:

Product	A_1	A_2	A_3
Activation cost	\$170000	\$150000	\$100000

3. Change the mathematical program and the AMPL model to cater for both the fixed activation cost and for a minimum production batch:

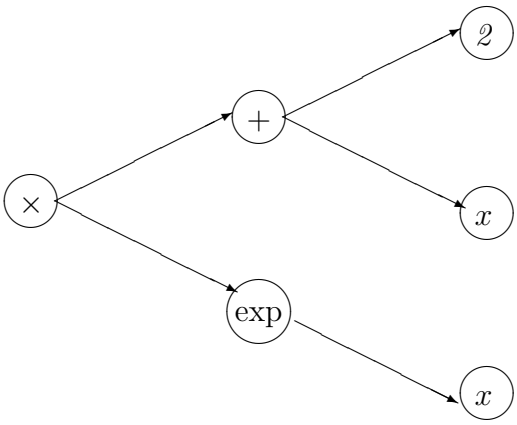
Product	A_1	A_2	A_3
Minimum batch	20	20	16

[*E. Amaldi, Politecnico di Milano*]

4.3 Checksum

An *expression parser* is a program that reads mathematical expressions (input by the user as strings) and evaluates their values on a set of variable values. This is done by representing the mathematical

expression as a directed binary tree. The leaf nodes represent variables or constants; the other nodes represent binary (or unary) operators such as arithmetic (+, -, *, /, power) or transcendental (sin, cos, tan, log, exp) operators. The unary operators are represented by a node with only one arc in its outgoing star, whereas the binary operators have two arcs. The figure below is the binary expression tree for $(x + 2)e^x$.



The expression parser consists of several subroutines.

- `main()`: the program entry point;
- `parse()`: reads the string containing the mathematical expression and transforms it into a binary expression tree;
- `gettoken()`: returns and deletes the next semantic token (variable, constant, operator, brackets) from the mathematical expression string buffer;
- `ungettoken()`: pushes the current semantic token back in the mathematical expression string buffer;
- `readexpr()`: reads the operators with precedence 4 (lowest: +,-);
- `readterm()`: reads the operators with precedence 3 (*, /);
- `readpower()`: reads the operators with precedence 2 (power);
- `readprimitive()`: reads the operators of precedence 1 (functions, expressions in brackets);
- `sum(term a, term b)`: make a tree $+ \begin{array}{l} \nearrow \; a \\ \searrow \; b \end{array}$;
- `difference(term a, term b)`: make a tree $- \begin{array}{l} \nearrow \; a \\ \searrow \; b \end{array}$;
- `product(term a, term b)`: make a tree $* \begin{array}{l} \nearrow \; a \\ \searrow \; b \end{array}$;
- `fraction(term a, term b)`: make a tree $/ \begin{array}{l} \nearrow \; a \\ \searrow \; b \end{array}$;
- `power(term a, term b)`: make a tree $\wedge \begin{array}{l} \nearrow \; a \\ \searrow \; b \end{array}$;
- `minus(term a)`: make a tree $- \rightarrow a$;
- `logarithm(term a)`: make a tree make a tree $\log \rightarrow a$;

- `exponential(term a)`: make a tree make a tree exp $\rightarrow a$;
- `sine(term a)`: make a tree make a tree sin $\rightarrow a$;
- `cosine(term a)`: make a tree make a tree cos $\rightarrow a$;
- `tangent(term a)`: make a tree make a tree tan $\rightarrow a$;
- `variable(var x)`: make a leaf node x;
- `number(double d)`: make a leaf node d;
- `readdata()`: reads a table of variable values from a file;
- `evaluate()`: computes the value of the binary tree when substituting each variable with the corresponding value;
- `printresult()`: print the results.

For each function we give the list of called functions and the quantity of data to be passed during the call.

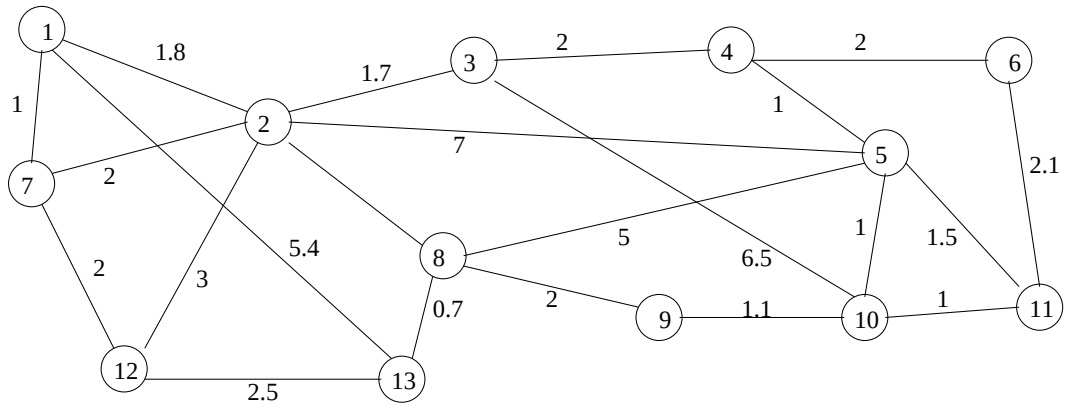
- main: readdata (64KB), parse (2KB), evaluate (66KB), printresult(64KB)
- evaluate: evaluate (3KB)
- parse: gettoken (0.1KB), readexpr (1KB)
- readprimitive: gettoken (0.1KB), variable (0.5KB), number (0.2KB), logarithm (1KB), exponential (1KB), sine (1KB), cosine (1KB), tangent (1KB), minus (1KB), readexpr (2KB)
- readpower: power (2KB), readprimitive (1KB)
- readterm: readpower (2KB), product (2KB), fraction (2KB)
- readexpr: readterm (2KB), sum (2KB), difference (2KB)
- gettoken: ungettoken (0.1KB)

Each function call requires a bidirectional data exchange between the calling and the called function. In order to guarantee data integrity during the function call, we require that a checksum operation be performed on the data exchanged between the pair (calling function, called function). Such pairs are called *checksum pairs*. Since the checksum operation is costly in terms of CPU time, we limit these operations so that no function may be involved in more than one checksum pair. Naturally though, we would like to maximize the total quantity of data undergoing a checksum.

1. Formulate a mathematical program to solve the problem, and solve the given instance with AMPL.
2. Modify the model to ensure that `readprimitive()` and `readexpr()` are a checksum pair. How does the solution change?

4.4 Network Design

Orange is the unique owner and handler of the telecom network in the figure below.



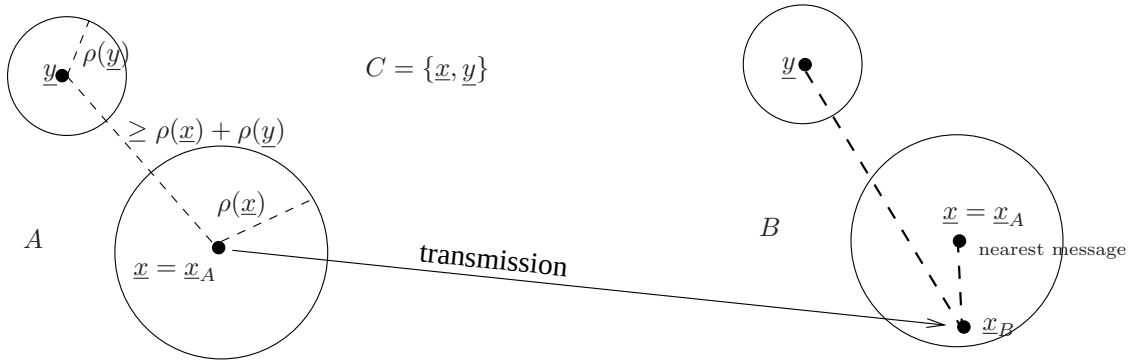
The costs on the links are proportional to the distances $d(i,j)$ between the nodes, expressed in units of 10km. Because of anti-trust regulations, Orange must delegate to SFR and Bouygtel two subnetworks each having at least two nodes (with Orange handling the third part). Orange therefore needs to design a backbone network to connect the three subnetworks. Transforming an existing link into a backbone link costs $c = 25$ euros/km. Formulate a mathematical program to minimize the cost of implementing a backbone connecting the three subnetworks, and solve it with AMPL. How does the solution change if Orange decides to partition its network in 4 subnetworks instead of 3?

4.5 Error correcting codes

A message sent by A to B is represented by a vector $\underline{z} = (\underline{z}_1, \ldots, \underline{z}_m) \in \mathbb{R}^m$. An *Error Correcting Code* (ECC) is a finite set C (with $|C| = n$) of messages with an associated function $\rho : C \to \mathbb{R}$, such that for each pair of distinct messages $\underline{x}, \underline{y} \in C$ the inequality $||\underline{x} - \underline{y}|| \geq \rho(\underline{x}) + \rho(\underline{y})$ holds. The *correction radius* of code C is given by

$$R_C = \min_{\underline{x} \in C} \rho(\underline{x}),$$

and represents the maximum error that can be corrected by the code. Assume both A and B know the code C and that their communication line is faulty. A message $\underline{x}_A \in C$ sent by A gets to B as $\underline{x}_B \notin C$ because of the faults. Supposing the error in $\underline{x}_B$ is strictly less than R_C, B is able to reconstruct the original message $\underline{x}_A$ looking for the message $\underline{x} \in C$ closest to $\underline{x}_B$ as in the figure below.



Formulate a (nonlinear) mathematical program to build an ECC C of 10 messages in $\mathbb{R}^12$ (where all message components are in $[0, 1]$) so that the correction radius is maximized.

4.6 Selection of software components

In this example we shall see how a large, complex Mixed-Integer Nonlinear Programming (MINLP) problem (taken from [6]) can be reformulated to a Mixed-Integer Linear Programming (MILP) problem. It can be subsequently modelled and solved in AMPL.

Large software systems consist of a complex architecture of interdependent, modular software components. These may either be built or bought off-the-shelf. The decision of whether to build or buy software components influencese the cost, delivery time and reliability of the whole system, and should therefore be taken in an optimal way. Consider a software architecture with n component slots. Let I_i be the set of off-the-shelf components and J_i the set of purpose-built components that can be plugged in the i-th component slot, and assume $I_i \cap J_i = \emptyset$. Let T be the maximum assembly time and R be the minimum reliability level. We want to select a sequence of n off-the-shelf or purpose-built components compatible with the software architecture requirements that minimize the total cost whilst satisfying delivery time and reliability constraints.

Chapter 5

Log analysis architecture

Some firms currently handle project management in an innovative way, letting teams interact freely with each other whilst trying to induce different teams and people to converge towards the ultimate project goal. In this "liberal" framework, a continual assessment of team activity is paramount. This can be obtained by performing an analysis of the amount of read and write access of each team to the various project documents. Read and write document access is stored in the log files of the web server managing the project database. Such firms therefore require a software package which reads the webserver log files and displays the relevant statistical analyses in visual form on a web interface.

Propose a detailed software architecture consistent with the definitions, goals and requirements listed in Sections 5.1, 5.2, 5.3.

5.1 Definitions

An *actor* is a person taking part in a project. A *tribe* is a group of actors. A *document* is an electronic document uploaded to a central database via a web interface. Documents are grouped according to their semantical value according to a pre-defined map which varies from project to project. There are therefore various *semantical zones* (or simply *zones*) in each project: a zone can be seen as a semantically related group of documents.

A *visual map* of document accesses concerning a set of tribes T and a set of zones Z is a bipartite graph $B_T^Z = (T, Z, E)$ with edges weighted by a function $w : E \to \mathbb{N}$ where an edge $e = \{t, z\}$ exists if the tribe t has accessed documents in the zone z, and $w(e)$ is the number of accesses. There may be different visual maps for read or write accesses, and a union of the two is also envisaged.

A *timespan* is a time interval $\bar{\tau} = [s, e]$ where s is the starting time and e is the ending time. Visual maps clearly depend on a given timespan, and may therefore be denoted as $B_T^Z(\tau)$. For each edge $e \in E$ we can draw the coordinate *time graph* of $w(e)$ changing in function of time (denoted as $w_e(\tau)$ in this case).

5.2 Software goals

The log scanning software overall user goals are:

1. given a tribe t and a timespan $\bar{\tau}$, display a per-tribe visual map $B_{\{t\}}^Z(\bar{\tau})$;

2. given a zone z and a timespan $\bar{\tau}$, display a per-zone visual map $B_T^{\{z\}}(\bar{\tau})$;
3. given a timespan $\bar{\tau}$, display a global visual map $B_T^Z(\bar{\tau})$;
4. given a timespan $\bar{\tau}$ and an edge $e = \{t, z\}$ in $B_T^Z(\bar{\tau})$, display a time graph of $w(e)$.

The per-tribe and per-zone visual maps can be extended to the per-tribe-pair, per-tribe-triplet, per-zone-pair, per-zone-triplet cases.

5.3 Requirements

The technical requirements of the software can be subdivided into three main groups: (a) user interaction, (b) log file reading, (c) computation and statistics.

5.3.1 User interaction

All user interaction (input and output) occurs via a web interface. This will:

1. configure the desired visual map (or time graph) according to user specification (input action);
2. delegate the necessary computation to an external agent (a log database server) and obtain the results (process action);
3. present the visual map or time graph in a suitable graphical format (output action).

5.3.2 Log file reading

Log file data will be gathered at pre-definite time intervals by a daemon, parsed according to the log file format, and stored in a database. The daemon will:

1. find the latest entries added the log files since last access (input action);
2. parse them according to the log file format (process action);
3. write them to suitable database tables (output action).

5.3.3 Computation and statistics

Actually counting the relevant numbers and types of accesses will be carried out by a database engine. This will receive a query, perform it, and output the desired results.

Chapter 6

A search engine for projects

This large-scale example comes from an actual industrial need. An industry manager once mentioned to me how nice it would be to have a search engine for projects, and how easy their work would be if they were able to come up with relevant past data "at a glance" whenever a decision on a new project has to be taken. Although this example does not use UML (although it does use some diagrams inspired to UML), it employs some novel, partially automatic graph reformulation techniques for manipulating the software architecture graph. This example also shows how optimization techniques and mathematical programming are useful tools in software architecture.

6.1 The setting

T-Sale is a large multinational firm which is often employed by national governments and other large institutions to provide very large-scale services. They will secure contracts by responding to the prospective customers' public tenders with commercial offers that have to be competitive. The upper management of T-Sale noticed some inefficiencies in the way these commercial offers are put together, in that very often the risk analysis are incorrect. They decided that they could improve the situation by trying to use stored information about past projects. More precisely, T-Sale keeps a detailed project database which allows one to see how an initial commercial offer became the true service that was eventually sold to the customer. The management hope that the preliminary customer requirements contained in the public tender may be successfully matched with the stored initial requirements to draw some meaningful inference on how the project actually turned out in the past.

T-Sale wants to enter into a contract with a smaller firm, called VirtualClass, to provide the following service, which was expressed in very vague terms from one senior vice-president of T-Sale to VirtualClass' sales department.

> *We want a sort of "Google" for starting projects. We want to find all past projects which were similar at the initial stage and we want to know how they developed; this should give us some idea of future development of the current project.*

VirtualClass must estimate the cost and time required to complete this task, and make T-Sale a competitive offer. Should T-Sale accept the offer, VirtualClass will then have to actually plan and implement the system. Note:

1. The commercial offer needs to be drawn quickly. The associated risks should be assessed. It should be as close as possible to the delivered product.

2. In general, the software engineering team should follow the "V" development process (left branch) for planning the system, as shown in Fig. 6.1. We shall limit the discussion to the leftmost branch of the "V" process.

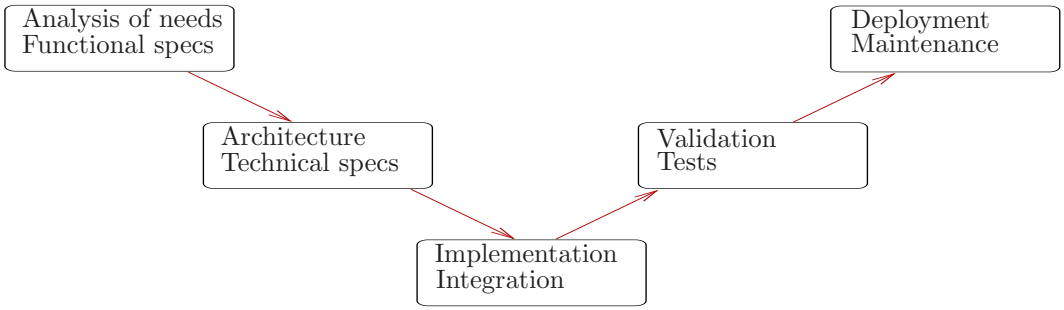


Figure 6.1: The "V" development process.

6.2 Initial offer

6.2.1 Kick-off meeting

Aims of the meeting:

1. Formalize the customer requirements as much as possible
   (a) What is the deliverable, i.e. what is actually sold to the customer?
   (b) What is the first coarse "common-sense" system breakdown?
2. What data is needed from T-Sale's databases?

6.2.2 Brainstorming meeting

Aims of the meeting:

1. propose ideas for a system plan with sufficient details for a rough cost estimate;
2. collect these ideas in a formal document;
3. decide on a sexy project name.

6.2.3 Formalization of a commercial offer

Aims of the meeting:

1. write a document (for internal use) which gives a rough overview of the system functionalities and of the system breakdown into sub-systems and interdependencies;
2. write a document (for internal use) with projected sub-system costs (complexity) and a rough risk assessment;
3. write a commercial offer to be sent to T-Sale with functionalities and the total cost.

6.3 System planning

We shall now suppose that T-Sale accepted VirtualClass' offer and is now engaged in a contract. The next step is to actually plan the system. The contract clearly states that T-Sale is under obligation to provide T-Sale with database details, which are shown in Fig. 6.2.

6.3.1 Understanding T-Sale's database structure

Aims of the meeting: analysis and documentation of T-Sales' database structure. Note that the project's *condition* contains information about whether the project was a success or a failure, and other overall properties. Make sure every software engineer understands the database structure by answering the following questions:

1. How do we find the main occupation of an employee?
2. How do we find the expertises of an employee?
3. How do we find the condition of a project?
4. How do we find how many times a project was changed?
5. How do we find whether a project was paid for on time or late?
6. How do we find whether a customer usually pays on time or late?
7. How do we verify that the cost of all phases in a project sums up to the total project cost?
8. How do we evaluate the cost in function of time during the project's lifetime?
9. How do we discriminate between the phase cost due to human resources and the cost due to other reasons?
10. How do we find the expertises (with their levels) that were necessary in a given project?
11. How do we find out the abilities and skills (with their levels) that were necessary in a given project?
12. How do we find out which teams were most successful?
13. How do we find out the most dangerous personal incompatibilities?

6.3.2 Brainstorming: Ideas proposal

The commercial offer quotes: "Given some meaningful key-words or other well-defined indicators in the description of a new project, we want to classify it by some quantitative indices [...]". Such concepts as "meaningful key-words or other well-defined indicators" and "quantitative indices" are not well-defined, and therefore pose the most difficult problem to be solved in order to arrive at a software architecture. In order to solve the problem, a brainstorming meeting is called.

Aim of the meeting:

1. find a set of well-defined new project indicators which are suitable for searching similar terms in the T-Sale database;
2. find a set of quantitative indices to be computed using the T-Sale database information, which should shed light on the future life cycle of the new project;
3. document all ideas spawned during the meeting in a formal document.

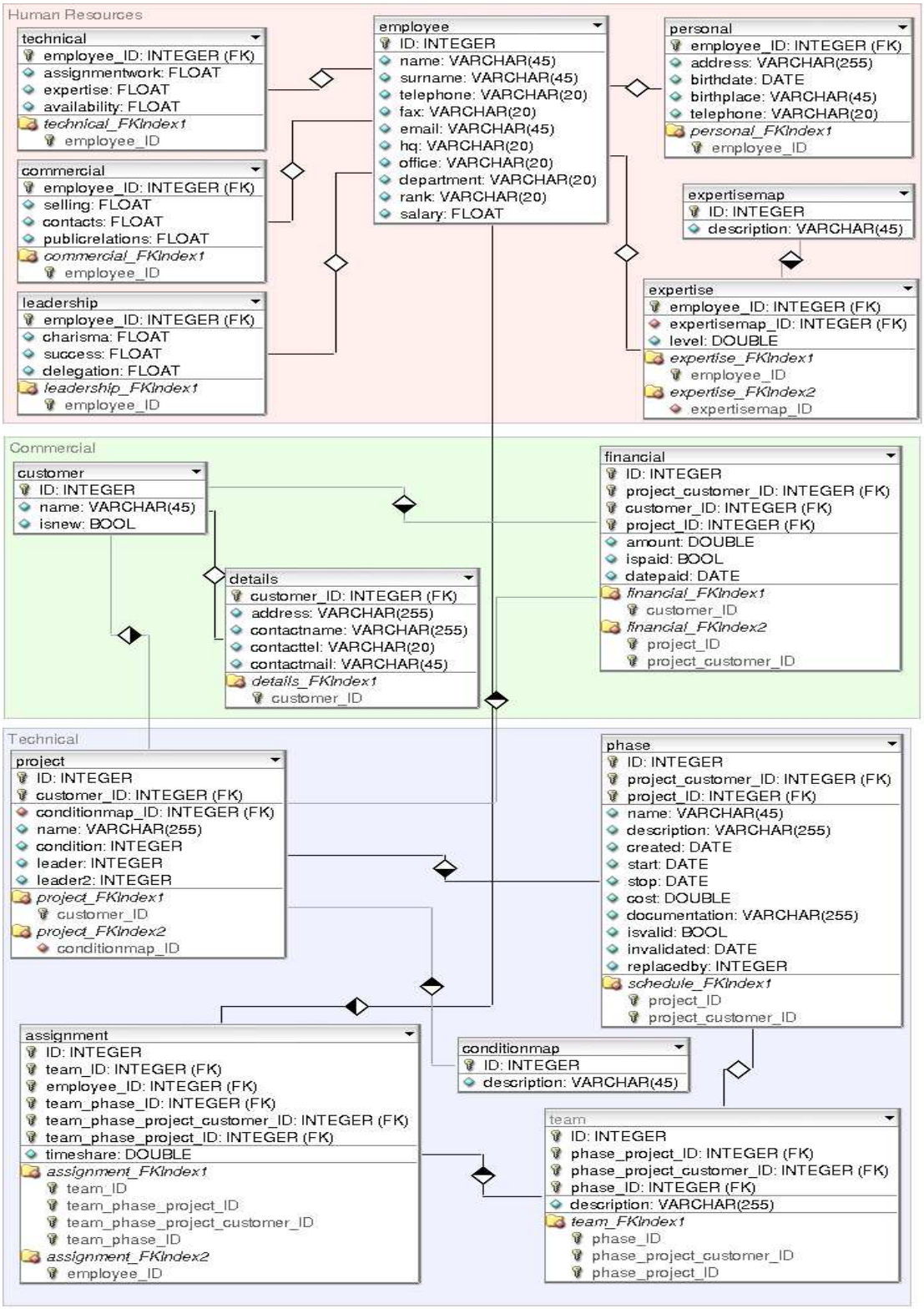


Figure 6.2: T-Sales' database structure.

6.3.3 Functional architecture

Propose a functional architecture for the software. This should include the main software components and their interconnections, as well as a break-down of the architecture into sub-parts so that development teams can be formed and assigned to each project part. Since system-wide faults arise from badly interacting teams, it is naturally wise to minimize the amount of team interaction needed.

6.3.4 Technical architecture

Propose a technical architecture detailing the inner working of each system component, as well as the system as a whole. This should include a class diagram and component APIs (application programming interfaces).

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