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Generalization/Specialization as a Basis for Software Specification

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ABSTRACT *This paper describes a software specification methodology based on the notion of concept specialization. The methodology, which is particularly useful for Information Systems, applies uniformly to the various components of such systems, such as data classes, transactions, exceptions, and user interfaces (scripts), and its goal is the systematic and structured description of highly detailed world models, where concepts occur in many variations. An example from the domain of university information systems is used to illustrate and motivate the approach.*

1. Introduction

Complaints about the high cost of software development and maintenance are now commonplace. Research in Programming Languages, Software Engineering, and Database Management attempts to deal with this problem by proposing tools and techniques for managing the ever increasing complexity of software. Many of these techniques are based on *abstraction mechanisms* that advocate the development of software in a stepwise fashion, each step involving only some of the details of the

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whole problem while others, hopefully the less relevant ones, are suppressed until some later step.[1]

For example, some current methodologies advocate the creation of a sequence of *models* ranging from the initial "real-world problem" to the final machine-executable program. This abstraction, called *Representation* in [SS79], involves implementation details and is supported by a number of languages and methodologies (*e.g.,* [PARN72] and [WLS76], among others). A second abstraction that has been advocated involves grouping a collection of units into a new conceptual unit (*Aggregation*). Software development through stepwise refinement [WIRT71] is based on this abstraction and offers decomposition as a methodological tool for building complex systems. This chapter focuses on *conceptual modelling*, *i.e.,* the specification of models that are closer to the human's conception of reality than to the machine's representation, and proposes a stepwise methodology based on *concept specialization.* In this case, the abstraction involves factoring out the commonalities in the description of several concepts into the description of a more general concept, and the refinement process reintroduces these details by specifying the ways in which a more specialized concept differs from the more general one. This methodology, which we call *taxonomic specification*, is complementary to stepwise refinement and methodologies based on Representation, and we feel that it is particularly appropriate when there are a large number of relatively simple, but interrelated, facts to be captured.

Section 2 elaborates on the notions of "model" and "abstraction," and Section 3 discusses Generalization as an abstraction mechanism and compares our version to others that have been proposed in the literature. In Section 4 we present a long example using a language along the lines of TAXIS[2] [MBW80] [WONG81] to illustrate the nature and the virtues of taxonomic specification. Section 5 sketches scripts that facilitate the description of the user dialogues that need to be supported by the system under design, and Section 6 discusses exceptions and an exception-handling mechanism that can be used as a tool in cases of over-abstraction. Finally, Section 7 presents conclusions and directions for further research.

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[1] The term "abstraction" is used here in a more general sense than usual in the field of Programming Languages, where its meaning is usually that of "representation abstraction," as that notion is defined below.

[2] TAXIS is a programming language for the design of interactive information systems, such as on-line inventory control and airline reservations, which supports taxonomic programming and offers many of the features discussed in the rest of the chapter.

2. Models and Abstractions

The observation that a computer system constitutes a model of a "world" or "slice of reality" about which it contains information has been made repeatedly in the literature (*e.g.*, [ABRI74] [BC75] [WILS75]), and is most obvious in the case of information systems. This observation motivates our first axiom: in a substantial number of cases, the process of software specification can be viewed as the process of building an accurate model of some enterprise. In order to facilitate the task of the modeler, as well as communication with the eventual users, we also assume that these models should reflect naturally and directly the users' conceptualization of the universe of discourse.

Unfortunately, the term "model" has several different technical meanings and it seems appropriate to contrast them with the sense used in this chapter.

The term receives its most precise and technical sense in the field of mathematical logic where, given a set of axioms and their deductive consequences, one interprets them in terms of a "model" (*i.e.*, a set of mathematical entities and relations which satisfy the axioms). This notion underlies in one way or another all other uses of the term, but in this technical sense its use is restricted to the theory of mathematical logic.

Two other uses of the term, namely as an analogue device (*e.g.*, a wind-tunnel model of an airplane) and as a mathematical model (*e.g.*, Maxwell's equations as a model of electricity) are common in science and engineering, but they are quite distinct from the term as used in this chapter.

From the cognitive sciences we obtain the notion of "conceptual model," which is much closer to what we want. Such a model consists of a number of symbol structures and symbol structure manipulators which, according to a rather naive mentalistic philosophy, are supposed to correspond to the conceptualizations of the world by human observers. This view appears to underlie work on "semantic data models" (*e.g.*, survey in [BORG82b]) and "knowledge representation" (*e.g.*, overviews in [BD81] and [MYLO81]).

Another sense of the term "model" is current in the area of Data Base Management Systems under the guise of "data model." A *data model* (see [TL82] for example) specifies the rules according to which data are structured and what associated operations are permitted on them. The traditional data models underlying commercial Database Management Systems consider as data only strings and numbers, and they are concerned primarily with the manner in which data is accessed by the user (in some cases reflecting how data is stored in the computer), and have little or no regard for the *interpretation* process required to make *information* out of *data*.

Since our concern here is with human oriented models of a world, we adopt the "conceptual model" sense of the term rather than one of the others.

If one accepts the need for conceptual models he is immediately faced with the problem of identifying the constructs that facilitate their creation. Not surprisingly, many of the proposed constructs have their roots in epistemological methods for organizing knowledge.

Abstraction is a fundamental conceptual tool used for organizing information. The following are just a few aspects of abstraction that are useful in describing complex conceptual models:

- *Classification.* Grouping entities that share common characteristics into a *class* over which uniform conditions hold. The class `PERSON`, for example, can be derived from the entities `john smith`, `mary brown`, *etc.,* through classification. The inverse of Classification, *Instantiation*, can be used to obtain other entities that conform to the constraints associated with the definition of the class `person`.

- *Aggregation.* Treating a collection of concepts as a single concept. For example, `person` could be thought of, rather naively, as an aggregation of its `name`, `address`, and `profession`. *Decomposition* is the opposite of Aggregation since it decomposes a class into its constituent parts.

- *Generalization.* Extracting from one or more given classes the description of a more general class that captures the commonalities but suppresses some of the detailed differences in the descriptions of the given classes. `Employee`, for instance, is a generalization of the classes `secretary`, `trucker`, and `accountant`. The process that has the opposite effect to Generalization (*i.e.,* creates a new class by introducing additional detail to the description of an existing one) is called *Specialization.*

There are other abstraction mechanisms, such as "normalization" (suppression of details that deal with deviations from the norm and emphasis of details that deal only with the normal or ordinary circumstances [BORG82a]) but the three above have received the most attention. Conceptual models of complex worlds are bound to be large if they are to account for sufficiently many properties of their subjects. The abstraction mechanisms discussed above offer both *organizational principles* and *design methodologies* for conceptual models.

Not surprisingly, each of these mechanisms, as well as the representation abstraction noted in the introduction, has led to proposals for software development methodologies. For example, Representation has led to abstract data type-related methodologies and important programming languages such as Simula [DH72], CLU [LSAS77], Alphard [WLS76], *etc.* (See the chapter by Shaw.) These have been defined to support the development of software through the gradual introduction of implementation detail. Similarly, aggregation has led to proposals for the design of software through stepwise refinement (by decomposition) (*e.g.,* [WIRT71] [DIJK72]), and languages such as Pascal have been found suitable for supporting this abstraction. Object-oriented programming is based on classification and is supported by Simula and some of its successors, notably Smalltalk [INGA78] and Actors [HBS73]. Finally, generalization leads to methodologies that organize the collection of classes constituting a model into hierarchies (taxonomies). Simula (again!) and in a different context [SS77] follow this route.

Of course, a successful software development methodology has to employ as many of the above mentioned abstraction mechanisms as possible. For the purposes of research strategy, however, it seems fruitful to focus on one mechanism and to formalize it, examine its applicability, and study its usefulness; hence, this chapter concentrates on the notion of Generalization/Specialization.

3. Generalization/Specialization

We are interested in formulating a methodology for building conceptual models based on Generalization/Specialization. The key idea of such a methodology is that a model can be constructed by modelling first, in terms of classes, the most general concepts and tasks in the application area, and then proceeding to deal with sub-cases through more specialized classes. Models constructed through such a process have their classes structured into a *taxonomy* or so-called *IS-A hierarchy.* For example, when building a student enrollment system for a university, one might consider first the concepts of student and course and the task of enrolling a student for a course. Later, the designer can consider graduate and undergraduate students and courses, full- and part-time students, day and evening courses, and the rules and regulations that apply to these classes. Indeed, we believe that most situations of application programming, such as ones for student enrollment, inventory control, airline or hotel reservations, inherently involve *large* amounts of *simple* detail, and that taxonomies offer a fundamental tool for coping with such situations.

Taxonomies of classes have been used in one form or another in artificial intelligence, programming languages and databases for over a decade (*e.g.,* [QUIL68] [DH72]). However, each author formulates them differently. The rest of this section outlines the main points of view and contrasts them to the one adopted in the chapter.

One of the advantages of organizing descriptions into taxonomies is the notion of *inheritance*. Since instances of a subclass are generally also instances of its superclasses, there is no need to repeat the information specified in the description of a class for each of its subclasses, and their own subclasses, *etc.* As a result, taxonomic descriptions can be abbreviated, and some clerical errors can be avoided by reducing the amount of repetition in descriptions.

There are two basic ways to view the description one associates with a class such as `PERSON` (intended to model the concept of person). The first is that the description simply characterizes a prototypical instance of the concept, *i.e.*, a prototypical person. It follows from this view that some of the assertions of the description (*e.g.*, that a person has a telephone number) might be contradicted by a particular instance of the class (*e.g.*, `bill brown` who doesn't have a telephone number because he doesn't have a telephone). Much of the Knowledge Representation research within Artificial Intelligence views classes (concepts/frames/units/ . . .) in those terms. The second view treats the description associated with a class as asserting necessary conditions that must be satisfied by all of its instances. Simula and the semantic data models adopt this view. The consequences of this choice on the nature of taxonomies (IS-A hierarchies) are immediate.

1. *Class as prototype.* If class C *IS-A* class B (*i.e.*, C is a specialization of B and therefore lower down on the hierarchy) and B has some properties, these properties can be over-ridden in the definition of C. Thus even though "All birds fly" and "Penguins are birds," penguins do not necessarily fly (in fact they don't!). Inheriting properties from a more general class is done by default here (*default inheritance*), *i.e.*, only if the description of the more specialized class does not assert otherwise. The assertions associated with a class have an "unless-otherwise-told" or default nature.

2. *Class as template.* If C *IS-A* B and B has some properties, then necessarily C must have the same properties. Asserting that every bird flies implies, with this view, that penguins *can't* be birds since they don't fly. Thus inheritance of properties from a class to its specializations is now strict (*strict inheritance*).

We adopt the second view of what a class is, and, as we will see in Sections 5 and 6, treat exceptions through a separate exception-handling mechanism rather than by weakening the assertional force of a class definition.

There is still another choice to consider once one has made this decision. Neither Simula, nor the semantic data models that have been proposed, with the exception of TAXIS, allow a property to be "refined" as one specializes a class. For instance, if we have asserted that every person has an age between 0 and 120 (years) in the description of the class PERSON, we would like to refine this property to "every student has an age between 12 and 80 when PERSON is specialized to obtain STUDENT. With strict inheritance a new class inherits all the properties of its generalizations and it can also have new properties of its own. However, it cannot refine any of the properties of its generalizations along the lines suggested above.

We consider that an important modelling tool is the ability to refine properties of a class as one generates its specializations.

We would like to emphasize even at this stage that the utility of generalization hierarchies for software engineering is not limited to the use of inheritance, although this feature is often the most visible. In particular, the *construction* of the hierarchies systematizes and structures the *process of information/requirements gathering*, and since the hierarchies persist even after the system is designed, they provide an *organization* of the information that facilitates the *location of information* and the *estimation of the effect of changes* (*e.g.*, changes to a class description will affect all subclasses of that class) during program maintenance. Furthermore, the development of procedures through stepwise refinement by specialization down the IS-A hierarchy permits an incremental testing of such programs, in contrast to programs developed through stepwise refinement by decomposition [WIRT71], where only the final stage of the refinement is an executable program. In this chapter, we shall concentrate on the use of Generalization hierarchies in the description of Information Systems; we describe elsewhere the application of these ideas to requirements specification [GBM82] and verification [WONG81] [BORG81], among others.

4. Taxonomic Specification

As argued earlier, we view our task as having to describe the conceptual data objects and activities that occur in the domain of discourse, and their associated constraints. Throughout this section our ideas will be illustrated with examples from the student enrollment process at the University of Toronto. In order not to distract from the methodological aspects of this chapter, we have chosen to present the examples in a semiformal way, preferring a skeletal language augmented with English descriptions of programming language code; the interested reader is referred to [WONG81] and [MBW80] for details of a programming language into which these descriptions can be immediately translated. Better known languages such as Simula [DH72] and Smalltalk [INGA78], and recent systems such as Pie [BG80a], also support versions of the abstractions involved in our methodology.

Aggregation is supported by the notion of *property*—a function which, when evaluated for an entity, returns one of its components or, more vaguely, a related entity. For example, if "cs100" was some particular course, then *title*("cs100"), *limit*("cs100"), *size*("cs100") and *class-list*("cs100") might represent respectively the title of this course, 'Introduction to Programming,' the maximum and current enrollment in the course, say 800 and 647 respectively, and the list of students currently enrolled in "cs100." In the case of aggregation as applied to an activity, some properties would have as value those activities that would result from one step of decomposition as suggested by stepwise refinement. Other properties of an activity would indicate the participants in the activity, as well as possibly other "meta-information" such as its beginning time, deadline for completion, *etc.* For example, if "e" is the activity of enrolling the student "bilbo" into the course "cs100," then we might have *student*("e") = "bilbo," *course*("e") = "cs100" as the participants, and one of the component activities, say *p2*("e"), would add *student*("e") to the *class-list* of *course*("e").

Clearly, describing a model in terms of such specific "factual" information is hardly satisfactory for the purposes of software specification. In fact, the information required is of a "generic" nature, and this imposes limitations on the facts that the computer system might record. These are known as semantic constraints [HM75].

Classification provides one important means for introducing such generic information by allowing us to present both the properties applicable to all of the instances of a class and the constraints that restrict the possible values of these properties. For example, the definition of the class COURSE might include as properties *title, limit, size, class-list, instructor*, *etc.* Constraints on these would include at the very least an indication of the range classes of these functions, as well as possibly more complex limitations. For example, *size* might have 0 to 2000 as range, as well as the additional constraint that the *size* of the course must be no greater than its *limit* (constraint *course-limit* of COURSE). This kind of information is obviously closely related to the notions of type declaration in Programming Languages and to schema definition in Databases. The diagram in Figure 4.1 describes two classes of objects, STUDENT and COURSE, which will play a central role in our enrollment system.

Whereas classification of objects yields data class definitions, classification of activities yields transaction class definitions, similar to procedure declarations in Programming Languages. The participants in the activity play the role of formal parameters in procedure declarations; the constraints on the values of these properties include type information and initial, final, and invariant conditions, which act as 'well-formedness' constraints on the transaction invocation and execution. As suggested above, other properties indicate the subactions comprising the definition of the procedure. Figure 4.2 is a schematic description of the ENROL transaction class in our proposed student record system.

```
data class STUDENT with
  attributes
    name: PERSON_NAME;
    age: 12..80;
    home-address: ADDRESS;
    univ-address: ADDRESS;
    faculty: {Arts&Science, GradSchool, Medicine};
    status: {Full-time, Part-time}
    courses-taken: set of COURSE;
    taking-courses: set of COURSE;
end STUDENT;

data class COURSE with
  attributes
    title: STRING;
    dept: DEPARTMENT;
    limit: 0..2000;
    size: 0..2000;
    enrollment: set of STUDENT;
    level: {1st-year,...,4th-year,intro-grad,adv-grad};
    instructor: PROFESSOR;
  invariants
    course limit: (size ≤ limit);
end COURSE;
```

Figure 4.1 *Definition of STUDENT and COURSE Classes*

```
transaction ENROL with
  parameters
     s: STUDENT;
     c: COURSE;
  prerequisites
     Not-full?:  (c.size<c.limit);
  actions
     a1: add c to the list taking-courses of s;
     a2: add s to the enrollment-list of c;
     a3: increment size of c by 1;
end ENROL;
```

Figure 4.2. *The ENROL Transaction Definition*

Since defining the appropriate classes is an important aspect of our methodology we offer two heuristics for designers.

1. In general, properties, regarded as functions, are undefined everywhere except over the instances of the class they have been associated with, and usually every new class definition introduces several new properties; hence a new class ought to be introduced whenever

we desire a property whose domain of definition is not an already existing class.

2. Secondly, almost all semantic constraints are stated through quantification over the instances of classes (*e.g.,* all instances of STUDENT must have as *age* an instance of INTEGER in the range 12 to 80).

Additional expressive machinery occasionally may be needed but we feel that these heuristics are adequate for a large number of modelling situations.

Our methodology so far has only systematized and slightly extended normal practices in software specification. As stated above, we are particularly interested in extending this methodology to deal with situations where there are a multitude of minute details relating to many classes that share common characteristics. Specialization allows us to describe each *subclass* of a more general class by specifying only the additional details necessary for its definition, through the notion of inheritance described in Section 3. As discussed there, in specializing a class we can 1) "strengthen" any of the constraints stated for the parent class (*i.e.,* replace a constraint of the parent class, say A, with a stronger one B such that B implies A); 2) provide additional constraints; and/or 3) introduce new properties and related constraints. Figure 4.3 is a description of the subclass GRAD_STUDENT of STUDENT.

```
data class GRAD_STUDENT is a STUDENT with
  attributes
    faculty: {GradSchool};
    dept: DEPARTMENT;
    advisor:PROFESSOR;
    level: {MSc, PhD};
end GRAD_STUDENT;
```

Figure 4.3 *A Specialized Subclass of STUDENT*

Note that the *faculty* property of STUDENT was (consistently) refined in GRAD_STUDENT so that it admits only one value, GradSchool. Also, three new properties, *dept, advisor,* and *level* were introduced; these only apply to graduate students while all other properties of STUDENT are of course inherited by GRAD_STUDENT. It may be worth contrasting our notion of inheritance with that used in Simula or Smalltalk. Simula allows only complete textual inheritance in the sense that in describing subclasses one cannot alter the code described for the superclass, but must inherit it completely (strict inheritance). Smalltalk on the other hand uses default inheritance. Our description of Specialization above requires that the refined version of a constraint must not contradict the original one; this ensures that all instances of subclasses are also legal instances of all the classes higher up in the hierarchy. Finally, it appears that neither Simula nor Smalltalk allows multiple inheritance (*i.e.*, inheritance from several distinct classes), a feature that we shall find quite useful in describing transactions.

In the case of transactions, the specialization of parameters proceeds in the same way as that of properties for data classes. As far as component properties are concerned, one can either specialize the transaction class of which a property must be an instance, or provide additional properties. The example in Figure 4.4 illustrates the specialization of the transaction class ENROL whose instances have graduate students as the student *s* participant.

```
specialize ENROL (s : GRAD_STUDENT, c : COURSE)
  add
    prerequisite
      Advanced? (c.level ≥ 4th-year);
    action
      a4:  inform School of Graduate Studies
                about the enrollment;
end;
```

Figure 4.4 *Specializing the ENROL Transaction*

Here an additional prerequisite is added to ENROL for graduate students to ensure that they are not allowed to take courses that are below Fourth Year. There is also an extra action that will be carried out only during the enrollment of graduate students. We will henceforth use ENROL (*s* : C1, *c* : C2) to denote the subclass of ENROL whose instances have the student *s* in C1 and the course *c* in C2.

In order to provide a more convincing demonstration of the utility of specialization as a specification methodology, we present next a partial list of conditions on the enrollment of students in Computer Science courses. Many of these were actually required until recently at the University of Toronto, although some were not checked until the students were told that they had not taken the appropriate program and would have to take one or more additional courses! It would clearly be beneficial if these conditions were incorporated into any computerized student information system, and hence modelling these constraints becomes an important goal. For ease of reference, we have labeled each with a mnemonic name followed by a question mark, indicating that each of these will be a constraint predicate. The list in Figure 4.5 is clearly haphazardly drawn up and it is exactly our point that such restrictions should be gathered in a more systematic way by system designers, and hence our software development methodology should support such systematization. In this case, we have chosen to encode most, although not all, of these constraints as prerequisites of the

ENROL transaction. The understanding is that if any of these prerequisites is false, an *exception* will be raised and execution of the transaction will be suspended. (We leave unspecified for the moment what action should be taken to handle such exceptions.) As the first step in our description, we present in Figure 4.6 the prerequisites and actions of ENROL that apply to all students and all courses. This is in accord with our proposal that one ought to describe first the more general classes, and hence the constraints which apply to most objects.

Not-taken-before?	A student cannot take the same course more than once.
Permission?	An undergraduate student requires the permission of the instructor before taking a graduate course.
Part-time-min.?	Part-time students need not take any courses in any particular year.
At-least-4th-year?	Graduate students cannot take first, second, or third year courses.
Not-full?	A student cannot enroll in a course whose enrollment limit has been reached.
Undergrad-min.?	A full-time undergraduate must take at least 5 courses each year.
Undergrad-max.?	A full-time undergraduate may not take more than 6 courses in one year.
Not-excluded?	There exist groups of mutually exclusive undergraduate courses and an undergraduate may take at most one course from such a group.
Before-deadline?	Undergraduates must register in courses by October 13th.
Offered?	A student cannot take a course that is not offered at the time requested.
Has-preparation?	An undergraduate course may have prerequisites that an undergraduate student must have taken in previous terms.
Part-time-max.?	Part-time students may not take more than 3 courses a year.
Areas-OK?	A graduate Computer Science student must have taken courses in each of three major areas.
Another-1st-year?	At most 6 First Year courses may be counted toward the 22 required for a B.Sc. degree.

Specialist?	Arts & Science students desiring a specialist's degree must have taken the appropriate selection of courses.
Has-coreqs?	Certain undergraduate courses may require undergraduates to take other courses at the same time (*e.g.*, in mathematics).
Probation-max.?	An undergraduate student on probation may take no more than 5 courses a year.
Grad-max?	Graduate students should not take more than 6 half-courses a year.

Figure 4.5 Restrictions on Enrolling in Computer Science Courses

```
ENROL (s: STUDENT, c: COURSE);
  prerequisites
    Offered?;
    Not-full?;
    Not-taken-before?;
  actions
     a1: add c to the list taking-courses of s;
     a2: add s to the enrollment-list of c;
     a3: increment size of c by 1;
end ENROL;
```

Figure 4.6 Most General Definition of ENROL

In order to introduce further details about ENROL, we can first describe two subclasses of STUDENT, namely GRAD_STUDENT and UNDERGRAD_STUDENT. Since one of the properties of ENROL is the parameter *s*, supposedly an instance of STUDENT, we can describe two subclasses of ENROL: one for which *s* is restricted to be an instance of GRAD_STUDENT, another for which *s* is an instance of UNDERGRAD_STUDENT. In each case, we can introduce further constraints that must be checked before enrolling a student in a course (see Figure 4.7).

Similarly, we can distinguish subclass GRAD_COURSE and UNDERGRAD_COURSE of COURSE, and in the case of graduate courses we have a number of additional actions to be done in ENROL, as illustrated in Figure 4.8.

There are two important points to note here about the interpretation of ENROL ("bilbo," "cs100"), assuming "bilbo" is an instance of UNDERGRAD_STUDENT and "cs100" is an instance of GRAD_COURSE: by inheritance, this activity will have all the properties of ENROL(*s*: STUDENT, *c*: COURSE), ENROL(*s*: UNDERGRAD_STUDENT, *c*: COURSE), and ENROL(*s*: STUDENT, *c*: GRAD_COURSE), and by an obviously useful convention, all inherited prerequisites will be checked before any of the inherited actions will be executed. In this example multiple inheritance is obviously a useful tool for the designer of a system.

```
specialize ENROL(s: UNDERGRAD_STUDENT, c: COURSE);
   add
      prerequisites
        Before-deadline?;
        Not-too-many: Undergrad-max?;
end;

specialize ENROL (s: GRAD_STUDENT, c: COURSE);
   add
      prerequisites
        At-least-4th-year?;
        Areas-OK?;
        Not-too-many: Grad-max?;
      actions
        a4: inform School of Graduate Studies
                about the enrollment;
end;
```

Figure 4.7 *Some Specializations of ENROL*

```
specialize ENROL (s: STUDENT, c: GRAD_COURSE);
   add
      actions
        a6: issue to s a key to the library;
        a7: give s an unlimited $ computer account;
end;
```

Figure 4.8 *Another Specialization of ENROL*

Resuming the task of introducing the constraints in Figure 4.5, we can now consider specialization of ENROL where more than one parameter is specialized. As a result, we add additional constraints on ENROL(*s*: UNDERGRAD_STUDENT, *c*: UNDERGRAD_COURSE), ENROL(*s*: UNDERGRAD_STUDENT, *c*: GRAD_COURSE) and ENROL (*s*: GRAD_STUDENT, *c*: UNDERGRAD_COURSE), as in Figure 4.9.

Finally, by creating additional subclasses PART_TIME_STUDENT and STUDENT_ON_PROBATION of UNDERGRAD_STUDENT, we specialize the *Not-too-many?* prerequisite to *Part-time-max?* and *Probation-max?* respectively.

```
specialize ENROL(s: UNDERGRAD_STUDENT, c: GRAD_COURSE);
 add
    prerequisites
      Permission?;
end;

specialize ENROL(s: UNDERGRAD_STUDENT, c: UNDERGRAD_COURSE);
 add
    prerequisites
      Has-preparation?;
      Not-excluded?;
      Another-1st-year?;
end;

specialize ENROL(s: GRAD_STUDENT, c: UNDERGRAD_COURSE);
 add
    prerequisites
      At-least-4th-year?;
end;
```

Figure 4.9 Further Specializations of ENROL

A number of remarks are in order at this point. First, note that some restrictions, such as the minimum number of courses that a student must take, cannot be checked until a student has enrolled in all the courses he or she was going to take, and hence these restrictions should not be placed in the ENROL transaction. Instead, one may have a REGISTER transaction which requires as a parameter the list of courses that the student intends to take in that year, and the above conditions would then be prerequisites on this list of courses. Alternatively, after a certain date has passed, a transaction could be run automatically to check such constraints on the list of courses each student is taking. Secondly, note that since we treat data and transactions in a uniform manner, there is no reason why the conditions in Figure 4.5 could not be considered as invariant assertions for the classes of objects STUDENT and COURSE. In particular, they could be grouped around the *class-list* property of COURSE and properties *taking-courses* and *courses-taken* of STUDENT, and they could be introduced in a manner similar to the one used by describing the appropriate subclasses of STUDENT and COURSE. In this case however, violations of the constraints would be detected when the ENROL procedure attempts to insert a new element in the *taking-courses* list of a student, rather than at the time ENROL is originally invoked.

5. Scripts

As we have remarked in the previous section, not all conditions in Figure 4.5 can be accounted for as prerequisites of the ENROL transaction (for example: checking for co-requisites or for conditions involving a minimum number of courses where one needs to know what other courses the student is or will be enrolling in this year). Furthermore, a central attribute of many systems is the ability to communicate interactively with its users in order to obtain the data which "drives" the transactions. We must therefore be able to specify the communication protocols that make up the user interfaces.

For the above purposes we propose *scripts* (generalized processes that have elaborate communication and synchronization mechanisms for the system designer). The script formalism used is an adaptation of Zisman's Augmented Petri Nets [ZISM78] proposed for office automation systems and it is described in more detail in [BARR80]. Each script is essentially a Petri net that has parameters, local variables, and state transitions. In turn, each transition consists of conditions that must be true in order for the transition to fire, and actions that are to be carried out if the transition does fire. In order to enable communication, scripts can employ operators for *message passing* between a script and a terminal, or, more generally, between any two scripts. These operators are based on Hoare's primitives *give* and *take* [HOAR78], and they provide further ability for synchronization, especially when the clock is allowed to send "wake up" messages at desired times. Although much more elaborate communication mechanisms are being currently developed, we will consider here a message as simply a *form* that has text and slots that can be filled by the user (or some other script) and then sent off. (See [TSIC82] for a detailed discussion of the utility of forms as communication means in an office environment.)

To illustrate the use of scripts let us place *enrolling into courses* into a wider context. At our university, students register first with the university. This includes paying fees, selecting a program of studies that is "correct," *etc.* However, students take courses directly from the departments offering them, thus allowing the departments to have direct contact with students in order, for example, to sell them required lecture notes, lab materials, *etc.* Consider therefore the TAKE_COURSE script which describes the protocol for taking a course (see Figure 5.1).

The script is parameterized by the department *d*, which is supposedly offering the course, and it includes five states represented by circles and five state transitions represented by vertical bars. Each transition has associated conditions and actions, and these are separated by => on the diagrams. An instance of the TAKE_COURSE script is created by the secretary of the appropriate department whenever a student enrolls in a course. The initial transition on the script requests a description of the student *s* and the course *c*, which are properties of the script. Once this information has been received, the script proceeds with the process of enrolling the student for the course, and this includes expecting a grade from the instructor of the course. At the same time, the script is set up to expect and act on a "drop the course" request at any time while the student is taking the course. Following normal procedures for enrolling, once the student and the course are identified the script invokes the ENROL transaction and then awaits the message indicating the grade that the student has received in the course. We remark that this script "lives" until the final state is reached, which may be several months later, and that every student would have several such scripts, one for each course he is taking, thus requiring sophisticated use of the database for maintaining all this information.

```
parameters
  d : department;
locals
  s : student;
  c : course;
```

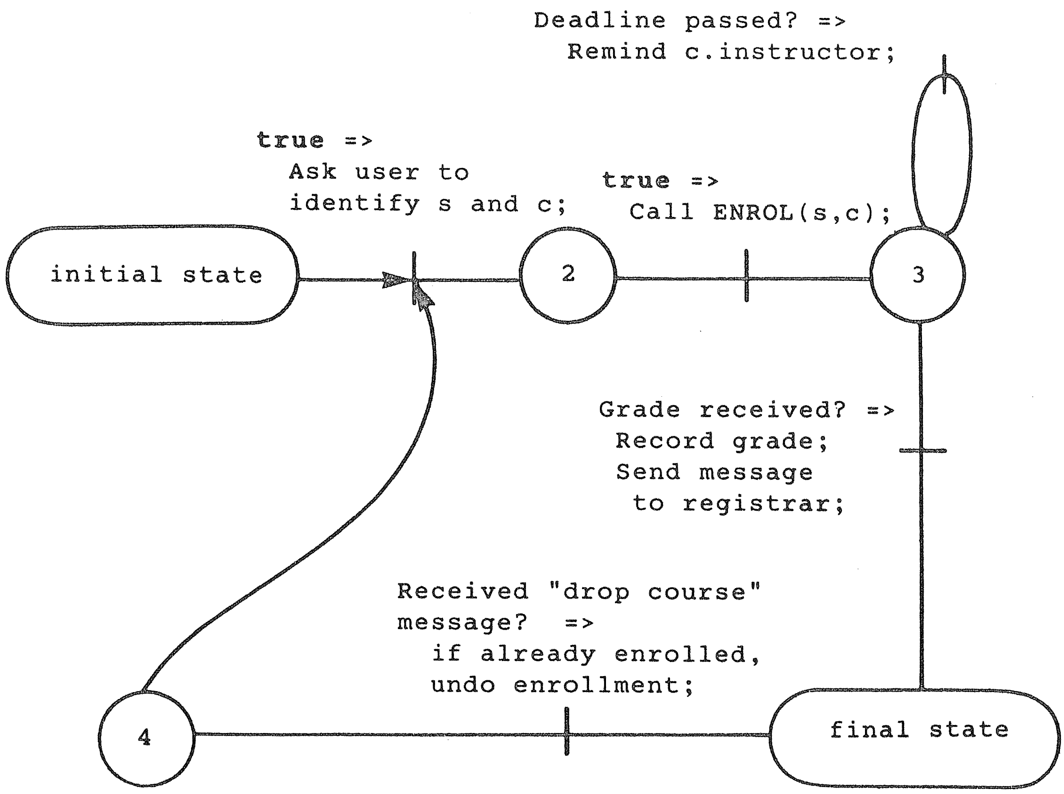


Figure 5.1 Diagram of the TAKE_COURSE Script

Scripts, like all other constructs, are treated as classes in our methodology. Thus their bodies (*i.e.*, their states and transitions), and also all other information associated with their definition is specified through properties that link a script to other classes. (Figure 5.2 shows the definition of the TAKE_COURSE script.)

```
script class TAKE_COURSE(d)
  parameters
    d:  DEPARTMENT;
  locals
    s:  STUDENT;
    c:  COURSE;
    grade:  {0..100};

  states
    initial:  initial_state;
    final:  final_state;
    others:  state_2, state_3, state_4;

  transitions
    obtain information:
      from initial state;
      to state_2, state_4;
      conditions   none
      actions   get s and c from user;
    enrollment:
      from state_2;
      to state_3;
      conditions   none;
      actions   call ENROL(s,c);
    late-grade:
      from state_3;
      to state_3;
      conditions deadline for grade for s,c passed?
      actions send message to instructor of c
    have-grade:
      from state_3;
      to state_4;
      conditions   sent a grade?
      actions   record grade and send message to
                          registrar;
    drop course:
      from state_4;
      to final state;
      conditions   sent "drop course" message?;
      actions   undo enrollment;
end TAKE_COURSE
```

Figure 5.2 Textual Description of TAKE_COURSE Script

It follows that transitions can be specialized in a manner similar to transactions, and more generally one can add new states and transitions in order to create a script that applies in more restricted circumstances than a given script. For example, the Engineering departments may require a mid-term mark to be recorded and mailed to each student;

this could be accomplished by specializing TAKE_COURSE (*d*: DEPARTMENT) to TAKE_COURSE (*d*: ENGINEERING_DEPT) by adding the script in Figure 5.3.

```
                true => call ENROL(s,c);

. . . 2                                          3

                      5
                            Received mid-term grade? =>
                              Record mid-term grade;

   Deadline for mid-term passed?  =>
     Remind c.instructor;
```

Figure 5.3 *Additions for TAKE_COURSE(d:ENGINEERING_DEPT)*

Before leaving this section we present a second example of a script that models the sequence of events from the time an undergraduate student registers for his *n*th ($1 \leqslant n \leqslant 4$) year of (university) study until the time he completes it (Figure 5.4). The basic protocol described by the script involves accepting information about the student, followed by the courses he proposes to take, then waiting for the grades he/she is assigned in these courses, and finally determining that the student has completed the year satisfactorily. Secondary protocols are also defined to take care of such contingencies as withdrawal from the program or late arrival of grades.

To summarize, scripts are useful in enforcing dynamic integrity constraints on transaction call sequences (*e.g.,* one can't receive grades until enrolled in a course), and in defining the format and the protocol of interactions with users. They are a natural place for exception-handling, including exceptions arising because of time delays, as will be seen in the next section.

For simple examples, the introduction of scripts as modelling tools may seem heavy-handed and perhaps unnecessary. There is evidence, however, that designing the environment within which a system will run, including its user interfaces, is one of the thorniest problems facing a system designer [CM79]. We consider this observation a sufficient justification of the introduction and use of scripts within our modelling framework.

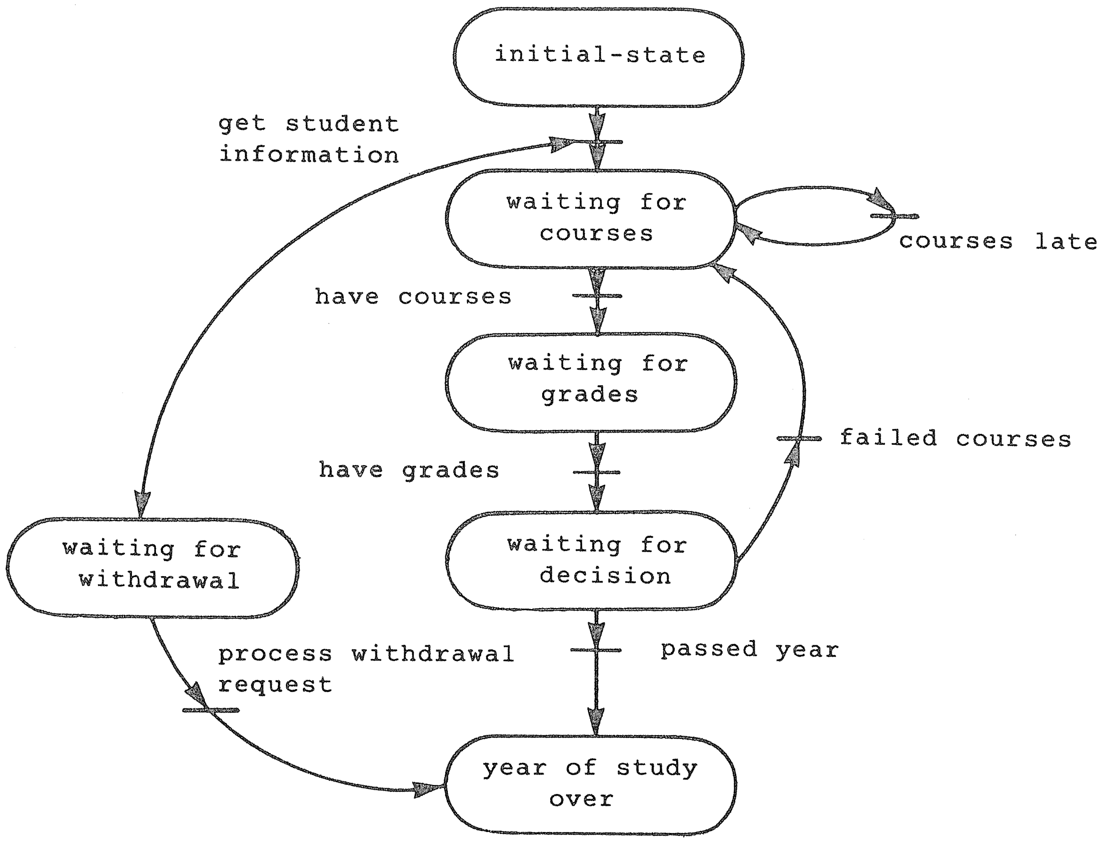


Figure 5.4 *The YEAR_OF_STUDY Script*

6. Exceptions

The ability to *manage exceptions* (*i.e.*, deal with over-abstraction) is characteristic of human behaviour and, we believe, of central importance in managing a multitude of details. Until recently this ability has been noticeably absent from computer application software. In our case, the traditional view dictates that a transaction such as ENROL should be aborted, hopefully with at least an error message, if any of its constraints (*e.g.*, prerequisites or restrictions on parameters) were not met. Alternatively, one might replace the prerequisites by successive IF-THEN conditionals, specifying in each case the course of action to be taken if the constraint were false. In addition to the limitation that this imposes on handling exceptions (see [LEVI77]), it appears to run counter to the "natural" flow of description: one has to constantly take detours from describing how students usually enroll in courses in order to say what is to be done in rare special cases. A more palatable alternative appears to be to adopt the convention that whenever a constraint (such as a prerequisite) evaluates to false, an *exception object* is raised (*i.e.*, is inserted as an instance of a special class). One can then describe in a separate pass the ways in which exceptions are to be handled. Furthermore, exceptions and exception-handlers can be described using the same methodology of concept specialization.

In order to simplify the discussion, we assume in our example that whenever a prerequisite is not satisfied, an instance of the exception labelled by the negation of the condition is raised (*e.g.,* if *Not-full?* is false then the exception *Full* is raised).

One possibility in specifying exceptions is to proceed methodically down the specialization hierarchy of ENROLs and specify which exceptions are raised when different conditions are violated. Alternatively, we may want to organize exceptions, including those raised by conditions that could not be checked in ENROL, into a specialization hierarchy organized along different lines than that of ENROL.[3] Figure 6.1 illustrates a hierarchy of exception classes constructed by answering the question "What can go wrong with enrolling in a course?" at various levels of generality.

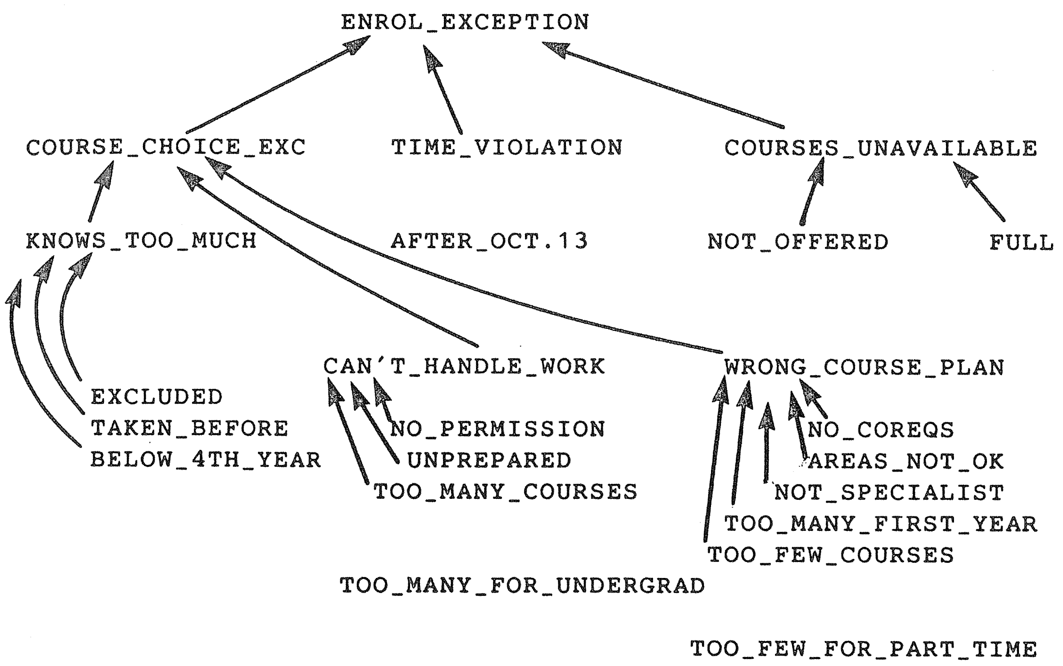


Figure 6.1 *Specialization Hierarchy for Exceptions*

The topmost exception class on the hierarchy, ENROL_EXCEPTION is intended simply to signal that an exception was raised during the execution of an ENROL transaction. Turning to its immediate subclasses, COURSES_UNAVAILABLE indicates that the course cannot be accommodated at the university, so one must abort the ENROL that caused the exception. Alternatively, the system may give the student

[3] Clearly, in doing this type design, computer aids are imperative when one checks to see whether all prerequisites have been accounted for.

information about when the course will next be given, and it might put the student on a waiting list before aborting. For TIMING_VIOLATIONS, students can petition to a special committee in order to be allowed to register late. In an automated office environment this might result in the ENROL being suspended while a PETITION is taking place. As far as COURSE_CHOICE_EX is concerned, there is nothing we can say that is applicable in all cases; one of the advantages of our methodology over more traditional approaches such as decision tables is that we do not have to say anything if we have no new information to add. However, considering subclasses of COURSE_CHOICE_EX, we note that instances of KNOW_TOO_MUCH should always be handled by "abort," since students should not be allowed to pick up credits gratis, while instances of CAN'T_HANDLE_WORK require petitioning again. In neither case need we say anything more about the subclasses of these two types of exceptions. Finally, the WRONG_COURSE_PLAN exceptions require distinctive individual treatment. For NO_COREQUISITE, the student must take the other course. For TOO_FEW_COURSES, he must take other courses, *etc.*

Turning to exception-handling, we assume that for each exception raised within a transaction *T*, the exception-handler, another transaction or script, is specified by the caller of *T*. The following specifications illustrate the exception-handling mentioned in the first half of this section.

To start with, we specify in TAKE_COURSE (*d*: DEPARTMENT), and, in particular, in association with the call to the ENROL transaction, the exception-handler to be used in case of an ENROL_EXCEPTION (Figure 6.2(a)). As indicated earlier, at this level exception-handling simply consists of a message to the user naming the exception that has been raised. Let's call this most general exception-handler EX_HANDLER (*e*: ENROL_EXCEPTION), shown in Figure 6.2(b). EX_HANDLER assumes that its exception argument has two associated properties, *std* and *crs*, through which one can determine the student and the course for which the exception was raised.

Dealing with some of the more specialized exceptions involves the adding of actions to be carried out by EX_HANDLER. For example, EX_HANDLER (*e*: COURSE_UNAVAILABLE) may output, in addition to the exception message, another message that specifies when the course is given in the future, and then abort the attempted enrollment (see Figure 6.3).

Other exceptions require additional states and transitions in EX_HANDLER. Thus TIMING_VIOLATION exceptions involve petitioning a committee and may eventually result in an enrollment (see Figure 6.4).

```
script class TAKE_COURSE(d:  DEPARTMENT)
  ....
  enrollment:
   ....
   actions call ENROL(s,c)
     for exception e∈ENROL_EXCEPTION with std←s, crs←c
     use EX_HANDLER(e)
     ....

     Modified enrollment transition in TAKE_COURSE
```

(a)

```
script class EX_HANDLER(e)
  parameters
    e:  ENROL_EXCEPTION;
  states
    initial:  initial_state;
    final:  final_state;
    others:  none;
  transitions
      send message;
        from initial state;
        to final state;
        conditions   none
        actions   send Class_of(e).message
  end EX_HANDLER;
```

Class_of(e) evaluates to the most specialized class **e** is an instance of, say C, and C.message evaluates to a(n error) message associated with that class as an attribute.

(b)

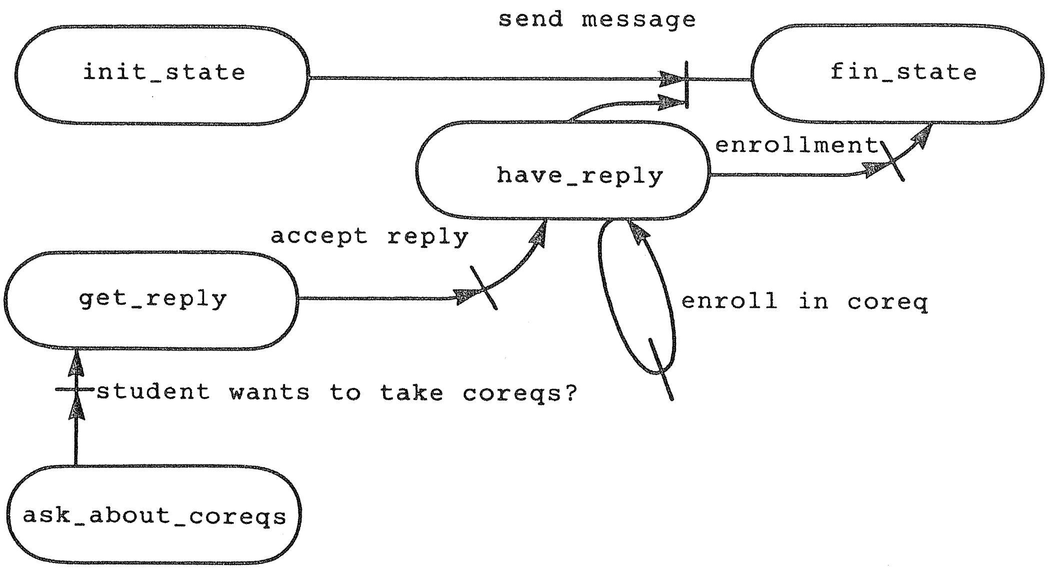
Figure 6.2 *Raising and Handling Exceptions*

```
specialize EX_HANDLER (e: COURSE_UNAVAILABLE);
 transitions
  send message:
   actions
     inform user when the course is given next;
     send "drop course" message to TAKE_COURSE
          (std,crs);
end;
```

Figure 6.3 *Specialization of an Exception-Handler*

```
specialize EX_HANDLER (e:  TIMING_VIOLATION);
  locals
    reply:  {YES,NO};
  states
    others:  awaiting_reply;
  transitions
    send message;
      from initial_state;
      to awaiting_reply;
      conditions none;
      actions
           send type (e).message;
           send petition (e.std, e.crs) to committee script;
    positive reply;
      from awaiting_reply;
      to final_state;
      conditions sent reply = YES?
      actions
           inform user;
           call ENROL(e.std,e.crs);
    negative reply;
      from awaiting_reply;
      to final_state;
      conditions sent reply = NO?
      actions
           inform user;
           send "drop course" message to TAKE_COURSE(std, crs);
end;
```

Figure 6.4 *Another Specialization of EX_HANDLER*



Ask_about_coreqs is also an initial state. Transition send message only fires if the reply has been negative; otherwise, enrollment fires.

Figure 6.5 *Exception Handler for Course Corequisites*

Among COURSE_CHOICE_EX exceptions, only WRONG_COURSE_PLAN requires special exception-handling facilities. For NO_COREQS exceptions, for example, EX_HANDLER must communicate with the user to determine whether the student is willing to enroll in all these courses. If he is, EX_HANDLER carries out all such enrollments and then proceeds with the enrollment originally requested. This specialization of EX_HANDLER is shown graphically in Figure 6.5.

We conclude this section by noting that the ability to describe scripts, exceptions, and exception-handlers within the same framework as provided for the normal data and transaction classes gives a pleasing uniformity and conceptual parsimony to the proposed methodology.

7. Conclusions

We have outlined and illustrated the principal elements of a software specification methodology that combines stepwise refinement by decomposition with concept specialization in order to introduce the multitude of details typically associated with large interactive systems. To recapitulate, the methodology suggests that the designer should start by defining the most general naturally occurring classes of objects and events in the domain. This is to be accomplished by the use of named properties that connect related concepts, and by the use of assertions that restrict the potential relationships. Further details of the proposed system are then introduced in successive iterations by describing subclasses of already presented classes and specializing transactions in order to deal with the objects in these classes.[4] The result is a hierarchy (taxonomy) of data, transaction, and script classes on which inheritance operates to abbreviate natural redundancy without losing the benefit of being able to check consistency. Once the usual/normal aspects of the system are described to some level of detail, the designer can describe, using the same methodology, the exceptions raised by the failure of assertions and their handling mechanism.

In evaluating the methodology, we feel that it is conducive to a natural style of description because it is oriented toward the *conceptual object* and *activities* occurring in the user's world. Our heuristics for identifying classes, and the suggestion of describing first general classes and then more specialized subclasses, provide some needed guidance to the designer. Similarly, the virtual specialization hierarchy that results

[4] Of course, this does not prevent one from introducing at any stage new classes, transactions, and scripts as they are needed.

when considering the possible specializations of each parameter for a transaction is a convenient conceptual rack on which to hang the details of the problem domain. In addition to its role of abridging descriptions, multiple inheritance, as illustrated in our example, allows one to think separately about independent aspects of the world (*e.g.*, undergraduate students and graduate courses) with inheritance taking care of their interaction. Finally, we feel that the systematic treatment of exceptions and exception-handlers within the same framework of data, transaction, and script classes supports another important abstraction principle: the ability to disregard the exceptional or unusual situations during the first pass in the design.

By developing program specifications according to the above methodology, one also gains some advantage in verifying the correctness of the final system. For example, having verified that a "general" transaction (*i.e.*, one high in the generalization hierarchy) maintains an invariant, one can often (because of inheritance) reuse this proof in demonstrating that the various specializations of the transaction also maintain the invariant (see [WONG81] [BORG81]).

Two other chapters in this book, those by King and McLeod and Brodie and Ridjanovic, also address the problem of designing complete database systems; hence a brief comparison of the three approaches is in order.

To begin with, there are a number of striking similarities in the general philosophy of the approaches taken, similarities due in no small part to the principles expressed in the title of this book: "conceptual modelling." Thus all three chapters start the design process with a conceptual model of the enterprise as seen by the system's eventual users. This model is meant to capture as much of the *semantics* of the real world as possible, certainly more than in traditional database design; in other words, all three chapters would be classified as work in "semantic/conceptual data models." Among others, this leads to an emphasis on modelling entities and their semantic relationships rather than on pure data organization. In a departure from most other semantic data models, all three emphasize the importance of modelling the *dynamic/behavioural*, not just the static parts of an enterprise, and the need to *integrate* these two facets of the description. Furthermore, all three chapters recognize the difficulties that arise in designing large, complex systems, and hence they emphasize the importance of a *methodology of design* that is inseparably linked to the modelling features offered. As a natural extension to this concern, the three research groups also offer a variety of computer tools that are meant to assist the designer in achieving a complete and accurate design.

Among the notable general differences are the fact that TAXIS, at least as presented here, focuses on design at one level only, while both the others consider design at several levels of detail. Thus in ACM/

PCM (see the chapter by Brodie and Ridjanovic), there is a general graphical schema, a more precise predicate-based technique for specification, and finally a functional technique for full details, wherever desired, while the "event model" of King and McLeod has an initial design schema, which drives the building of a conceptual schema, which in turn forms the basis of a physical design. On the other hand, through the notions of scripts, messages, exceptions, and exception-handlers, TAXIS probably addresses in detail a wider variety of aspects of an information system, though we should point out that the event model does model at least part of what scripts are intended to accomplish.

Although both this chapter and that of Brodie and Ridjanovic look for *uniformity* in the way objects and activities are modeled, they come up with different answers. ACM/PCM sees association of objects as paralleling iteration, and specialization of concepts corresponding to choice, while TAXIS's notion of iteration is not related to the abstraction principles, and specialization of transactions is quite similar in spirit to specialization of entities. A different attempt at uniformity shows up in the chapter of King and McLeod, in their novel attempt at incorporating the *modelling events* themselves into the model, thus bringing program maintenance into the same uniform framework.

Finally, the chapters can be distinguished by the basic metaphors which in some sense "drive" the design process. In the event model, the design schema describes mostly events and their interactions, and this drives the process of describing entities, *etc.* In contrast, the other chapters use the structure of the data descriptions to "drive" the description of the activities. In ACM/PCM, this is evident from the way that the actions associated with an application object are determined by its structure — the "context" (*e.g.*, in the Hotel-reservation actions). In TAXIS, on the other hand, the hierarchy of data classes "drives" the specialization of transactions, while the hierarchy of exceptions drives that of exception-handlers.

There are, of course, many other comparisons that could be drawn, but space limits us to those which we feel are most significant.

To conclude, we reiterate our belief that taxonomic organization is an essential human activity that allows us to cope with multitudes of detail. Our goal is to propose linguistic and computer tools that would support precisely such an organization during the development of a software system. Evidence of such tools can be seen in [BMW82] and in forthcoming MSc theses by B. Nixon and P. O'Brien. Since, in the end, the only demonstration of the importance of an idea is its successful practical use, our group has attempted to model in significant detail a number of applications in the university and hospital environments, with results presented in [WONG81] and in forthcoming theses by C. Di Marco and I. Buchan. Finally, research is still in progress on the use of these ideas for general requirements specification and for designing the language of interaction between users and a specific system.

The authors gratefully acknowledge the permission of North Holland Publishing Company to reproduce portions of an earlier version of this paper.

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