AN INNOVATIVE EDUCATIONAL ENVIRONMENT FOR THE INTERACTIVE LEARNING OF DATA STRUCTURES
From Algebraic Specification to Implementation

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Keywords: Virtual learning environments, Virtual universities and classrooms, Learning and teaching methodologies, Computer supported education, Interactive learning, Data structures, Algorithmic schemes, Algebraic specification.

Abstract: The high level of abstraction necessary to teach "data structures" and "algorithmic schemes" have been more than a hindrance to students. In order to make a proper approach to this issue, we have developed and implemented, during the last years, at the Computer Science Department of the Complutense University of Madrid, an innovative interactive learning system according to the new guidelines of the *European Higher Education Area*. In this paper, we present the new main contributions to this system. In the first place, we describe the tool called *Vedya* for the visualization of data structures and algorithmic schemes. In the second place, the *Maude* system to execute the algebraic specifications of abstract data types using *Eclipse*, by which it is possible to study from the more abstract level of a software specification up to its specific implementation in *Java*, thereby allowing the students a self-learning process.

1 MOTIVATION

The study of "data structures" and "algorithmic schemes" constitute one of the essential aspects of the academic formation of every engineer in Computer Science. Nevertheless, the high level of abstraction necessary to teach these topics occasionally hinders its understanding to students. In order to make a proper approach to this issue, we have developed and implemented, during the last years, at the Computer Science Department of the Complutense University of Madrid, an innovative interactive learning system according to the new guidelines of the *European Higher Education Area* and the teaching model focused on the student.

In this paper, we present the two main contributions to this system. On the one hand, the *Vedya* tool (Segura et al., 2008), a visualization tool by means of which it is possible to provide the student with a complete learning system of both the main data structures and the more relevant algorithmic schemes. On the other hand, the *Maude* system (Clavel and et al., 2006) for the execution of "algebraic specifications" of abstract data types using the language of formal specification provided by this system.
Thanks to the development environment *Eclipse* (*http://www.eclipse.org/*), we have obtained a fully complete system that is useful for the students as well as the professors, that allows to go from the most abstract level of data structures, provided by its algebraic specification in *Maude*, until its specific implementation in a modern programming language as happens with *Java*. All this learning process can be guided and overseen in a completely autonomous way by using the *Vedya* tool, through which it is possible to make enquiries about the documentation related to each of the algebraic specifications, to distinguish between the behavior of the structure and its different implementations through the use of different views or to browse information regarding the cost of the different implementations that have been proposed.

2 THE VEDYA TOOL

Vedya is an integrated interactive environment for learning data structures and algorithmic schemes. It covers the most common data structures: Stacks, queues, binary search trees, AVL trees, priority queues, and sorted and hash tables. Moreover, it also provides other different types of abstract data types, like one for an implementation of a "doctor's office".

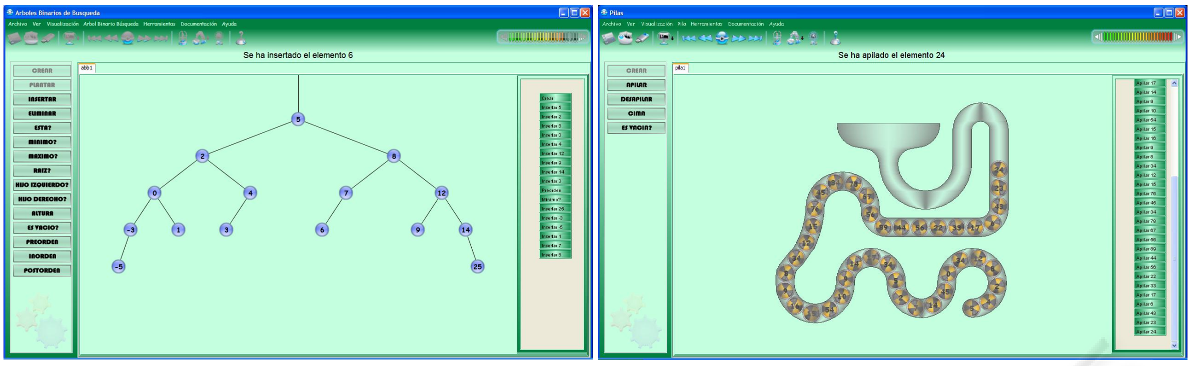

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Figure 1: Data structures and algorithmic schemes in the *Vedya* tool.

Concerning the algorithmic schemes, it covers the most common resolution methods (Brassard and Bratley, 1996; Cormen et al., 2001; Neapolitan and Naimpour, 2003): divide and conquer, dynamic programming, backtracking, and branch and bound. All data structures and algorithmic schemes taught in the related study courses are thereby integrated in the same environment: *Vedya* allows the execution of different data structures and several sequences of operations on the same structures at the same time making use of a multi-windows and multi-frame system.

Currently, there are two versions of the *Vedya* tool. The first version contains all the data structures and algorithmic schemes mentioned above while the new one offers a subset of them in a more attractive visual environment. This last version can be found at *http://www.fdi.ucm.es/profesor/rdelvado/*.

There are several options to use this tool. The main one is the interactive execution, but it is also possible to create simulations that are automatically executed, to visualize tutorials and to solve tests within the same environment. It also integrates a set of animations that show how data structures are used to solve certain problems. Figure 1 shows an example of the main windows for data structures (stacks and binary trees). The central panel is used to represent the structure. In the case of linear structures and binary trees, drawing facilities are offered to allow the expansion or contraction of the data structure or to move it over the screen to see the hidden parts. On the left, there is a list of the actions that can be executed. Partial non-allowed actions are disabled. The right panel shows the visualization of the actions that have been already executed. Next, the user may continue executing actions, go up on the sequence of actions to see previous states or she/he may use the stimulation facilities (standard buttons to execute, stop, move forward and move backwards at the top of the screen) to restart the sequence from the beginning. Notice that just above the central panel the result of the last action is shown.

There are two types of views: The one of data structure behavior to intuitively comprehend its operation, and one or several implementation views, either static or dynamic. On Figure 1 we show the specific behavior view of a stack. Representations of the static implementation based on an array and dynamic implementation based on pointers can be also shown.

Furthermore, the environment provides documentation about algebraic specification, the implementation code and the cost of each implementation. On the top of the screen, there is a menu that facilitates managing the system. We can create a new data structure, open an existing one or save the state of the editing one. We can also execute the operations on the data structure, use the simulation facilities and change the execution speed of the animations.

The main window for the execution of algorithmic schemes looks similar. We have implemented algorithmic schemes based on divide and conquer of binary search and quicksort; algorithmic schemes that solve backtracking problems (in its fractional and non-fractional version) based on dynamic programming; branch and bound, as well as the Dijkstra algorithm to obtain minimum path in a graph.

As has been previously mentioned, *Vedya* is complemented with tutorials on data types (stacks, queues, binary search trees, red-black trees, priority queues, and 2-3-4 trees) and animations of algorithms that show the use of a data structure to solve a problem (evaluation of an expression in postfix form, the transformation of an infix expression to a postfix one, breath-first tree transversal, checking of palindromes). Moreover, there are animations on graphs: To obtain the minimum spanning tree using the Prim and Kruskal algorithms and to compute minimum paths using the Dijsktra algorithm.

Finally, *Vedya* offers the *Vedya-Test* tool to solve

```
fmod STACK{X :: TRIV} is
  sort Stack{X} .
  op error    : -> Stack{X} .
  op error    : -> X$Elt .
  op empty    : -> Stack{X} .
  op push     : X$Elt Stack{X} -> Stack{X} .
  op pop      : Stack{X} -> Stack{X} .
  op top      : Stack{X} -> X$Elt .
  op isEmpty? : Stack{X} -> Bool .
  var P : Stack{X} .
  var E : X$Elt .
  eq pop(empty) = error .
  eq pop(push(E,P)) = P .
  eq top(empty) = error .
  eq top(push(E,P)) = E .
  eq isEmpty?(empty) = true .
  eq isEmpty?(push(E,P)) = false .
endfm
```

```
fmod QUEUE{X :: TRIV} is
  sort Queue{X} .
  op error    : -> Queue{X} .
  op error    : -> X$Elt .
  op empty    : -> Queue{X} .
  op enqueue  : Queue{X} X$Elt -> Queue{X} .
  op dequeue  : Queue{X} -> Queue{X} .
  op first    : Queue{X} -> X$Elt .
  op isEmpty? : Queue{X} -> Bool .
  var C : Queue{X} .
  var E : X$Elt .
  eq  dequeue(empty) = error .
  ceq dequeue(enqueue(C,E)) = empty   if isEmpty?(C) .
  ceq dequeue(enqueue(C,E)) = enqueue(dequeue(C),E))
                                      if not isEmpty?(C) .
  eq  first(empty) = error .
  ceq first(enqueue(C,E)) = E if isEmpty?(C) .
  ceq first(enqueue(C,E)) = first(C)
                                      if not isEmpty?(C) .
  eq  isEmpty?(empty) = true .
  eq  isEmpty?(enqueue(C,E)) = false
endfm
```

Figure 2: Algebraic specifications of stacks and queues in *Maude*.

tests. This tool can be independently executed and allows teachers to create, modify or delete questions in a database, and to create tests from the database of questions. The student visualizes the tests, solves them and obtains the correct solutions. Questions are grouped by subject-matter on the database, but it is possible to mix questions about different data structures in the same test. The last version of this tool can be also found at *http://www.fdi.ucm.es/profesor/rdelvado/*.

3 EXECUTION OF ALGEBRAIC SPECIFICATIONS IN MAUDE

For the execution of algebraic specifications, the language *Maude* (Clavel and et al., 2006) based on *rewriting logic* has been used. *Maude* is a high-level language and high-performance system supporting both equational and rewriting computation for a wide range of applications. *Maude* and its formal tool environment can be used in three mutually reinforcing ways: as a declarative programming language, as an executable formal specification language, and as a formal verification system. Moreover, (Clavel and et al., 2006) describes the equational specification of the data structures included in the *Vedya* tool now in *Maude* syntax (stacks, queues, lists, binary and search trees, AVL and 2-3-4 trees). The language is available for *Linux* and *MacOS* at *http://maude.cs.uiuc.edu*, and there are also extensions for its execution in *Windows* at *http://moment.dsic.upv.es*.

The specifications can be executed in *Eclipse* (*http://www.eclipse.org/*) by means of special "plug-ins" developed in the Department of Information Systems and Computation of the Technical University of Valencia (DISC-UPV) and in the Computational Languages and Sciences Department of the University of Málaga (DLCC-UMA). This environment facilitates the student its usage by integrating the text editor with the execution commands of the system. On the left, there appear the developed projects; the central part shows the editor and the execution panel of the system is on it; on the inferior part, the control panel that shows the result of the action. On the right part, the user can open other windows that allow the definition of different system options and depuration.

The basic element of a specification in *Maude* is a "module". The language allows defining the functional modules used to define the data types; system modules used to define rewriting systems and modules focused on objects that allow the usage of syntax of classes, objects and messages. The functional modules for stacks and queues are showed with more detail in Figure 2.

The language allows importing other modules, defining several data types, defining operations on the types and equations that define the behavior of those operations. The modules can be customized, using "theories" to such end in order to define the parameters and "views" to relate the formal parameter to the real parameter. The system has predefined the abstract data types most commonly used, as well as the most common theories and views:

```
view Int from TRIV to INT is
  sort Elt to Int .
endv

fmod STACK-INTEGERS is
  including STACK{vInt} .
endfm

fmod QUEUE-INTEGERS is
  protecting QUEUE{Int} .
endfm
```

As can be observed, the syntax is similar to the one used in several texts of algebraic specifications of data types (Weiss, 1998).

In order to execute the specification, the student enters the text in the editor; then, she/he executes the *Maude* system using the existing buttons in the console and enters the module. The system detects existing syntax errors and shows them on the console. Once the module shows no more errors, the student may reduce terms by using the equations of the module. To such end, the student may use the commands chart placed at the top of the screen or she/he may directly write the command in the editor and enter it into the system. For example, in order to obtain the first of a queue, we can reduce the term:

```
red first(enqueue(enqueue(empty, 5),4)).
```

This term must be reduced over the module of the queues using the integer number theory `INT`. In our example, this module is named: `QUEUE-INTEGERS`.

The possibility of reducing terms, in an automatic way, allows the students to carry out an initial test of their specifications by detecting many of the errors committed when defining the operations using equations.

Another greater advantage of executing the specifications is that the student comprehends the difference between the parameterized module and the instantiated module by being able to reduce terms on different modules. For example, a new module could be named `QUEUE-CHARACTERS` on which terms of type

```
red first(enqueue(enqueue(empty, 'a'),'c')).
```

can be easily reduced.
During the last academic courses, we have done practical classes on the data structures included in *Vedya*, which can be found at *http://www.fdi.ucm.es/profesor/rdelvado/*.

Other examples of data types, such as "medieval queues" or a "doctor's office" were also proposed (Weiss, 1998). In all of them, the aim was to define parameterized or instantiated data type with different theories. The practical classes are complemented with different terms that the student must reduce over some type of instantiated modules to prove the specification, as well as proposals to make little changes in some actions or erroneous definitions to detect them.

Taking into consideration that students from the second year were involved, just a few of the language facilities have been used. In superior courses where students have more knowledge on the subject, a richer language can be used (Clavel and et al., 2006) (e.g., many-sorted equational specifications, order-sorted equational specifications, equational attributes, and membership equational logic specifications).

4 FROM SPECIFICATION TO IMPLEMENTATION

The *Vedya* tool turns into a pedagogical instrument of high practical interest since it attempts to address the whole self-learning process of the main data structures, from the algebraic specification in *Maude* until the possible implementations in *Java*, within such a powerful and integrated environment as the one that has been described in the previous section by means of the *Eclipse* system.

The students have their first contact with the data structures that they are going to study by means of the usage of *Vedya*. For example, if their learning of data structures is focused on binary search trees or linear data structures, they will start learning the corresponding section of the tool, where they will be able to experiment, freely and on their own, each one of the actions offered by these structures (see Figure 1). In order to strengthen and evaluate this intuitive knowledge, the student has, in addition, the possibility of using the *Vedya-Test* tool.

Once the student has a clear idea of the informal behavior of the data structure, she/he may start working on the *Eclipse* system. The first step would be: to formally capture that intuitive knowledge she/he has obtained through the usage of *Vedya* in a specific algebraic specification written in *Maude* syntax. In order to facilitate this difficult step in the student's self-learning, she/he may use, interactively, the documentation that is included in the manual of the *Vedya* tool. Once the specification (see Figure 2) is entered into the *Eclipse* system, the student can now go on executing little tests using *Maude*, in order to check whether it coincides with the intuitive and informal notion of data structure from which he initially departed in *Vedya*. Such experience would allow the student to reach the high level of abstraction that is necessary in computer supported education for each formal specification of a software component, always based on the intuitive and experimental knowledge.

	Stacks 1	Stacks 2	Queues	Sequences	BST	AVL	RB	Heaps
Group A (130)	76.4%	82.5%	77.8%	65.6%	82.2%	84.9%	–	86.3%
Group B (59)	78.9%	83.6%	85.0%	63.6%	86.2%	87.7%	90.9%	90.2%
Group C (131)	76.2%	79.8%	73.5%	69.0%	83.5%	–	68.9%	86.8%

	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08
Not attended	57.6%	45.3%	42.3%	64.7%	50.8%	40.2%
Passed	15.3%	22.2%	20.2%	18.2%	30.1%	42.6%
Failed	27.1%	32.5%	37.5%	17.1%	18.9%	17.2%

Figure 3: Students answering the tests and percentage of correct answers.

Once the algebraic specification of the data structure is obtained, the next step would be to develop an implementation in an object-oriented programming language such as *Java*, by means of the facilities provided by the programming environment in *Eclipse*. This time, the student may use the algebraic specification that she/he has built, as if dealing with an authentic "instructions manual". The main advantage of our methodology is that the specification behaves now as a prototype of the data structures to be implemented, in a way that the student is able to find out the exact behavior for all those moments of doubt that may appear during the design process, even before she/he is able to compile the program. In order to be able to guide, in a more specific way, the step of specification to implementation, the student may make use again of the *Vedya* tool. This time, the student may access to the part that would correspond with the implementation of data structure that she/he is studying from the options menu (see Figure 1). From there, she/he may try different implementation possibilities based on arrays or pointers.

Once the student is familiar with the different implementations of the structure, she/he is finally ready to properly decide on a suitable representation in the *Java* language. The possibility of having understood and previously evaluated the different implementations by means of *Vedya* allows the student the possibility to acquire a clear knowledge of the *algorithmic cost* of the chosen implementation in *Java* for each specific operation of the data structure, so that this would also be a decisive criterion at the moment of designing its own implementations. In this part, the "*algorithmic schemes*" part of the *Vedya* tool plays an important role, since it allows the student to acquire a good programming methodology.

5 EVALUATION

In order to obtain a detailed evaluation of the usage of *Vedya* and *Maude* in our integrated system, we have proposed several tests related to the behavior, specification, implementation and application of the main data structures offered by the tool. We also collect students' opinion using *Vedya* in the "Data Structures" academic subject at the second year, and in the "Programming Methodology and Technology" subject at the third year, respectively.

The vast majority of our engineering and computer science students have taken an introductory programming course in the first academic year, typically in *Pascal*. Although the learning of the main algorithmic schemes and programming techniques is not a prerequisite to the subject of "Data Structures", many students choose to take it either prior to, or concurrent with, "Programming Methodology and Technology". As a result, although a pseudocode programming language is the assumed language for "Data Structures", many students have enough knowledge about *C++* or *Java* programming languages through the integrated programming laboratories of parallel academic courses and subjects.

Taking into account this profile, skills and background of our engineering and computer science students, we have proposed 8 tests in the *Virtual Campus* of the Complutense University of Madrid (*http://www.ucm.es/campusvirtual/CVUCM/*). The number of engineering students registered in the *Virtual Campus* was just over 320 distributed in three groups (130 in group A, 59 in group B, and 131 in group C). Figure 3 shows the number of the students who answered each of the tests in the corresponding group.

We observe that, from the second test on, the number of students becomes stable in a number lightly low to the number of students who access regularly to the *Virtual Campus*. These numbers, though seemingly high, are only between 23 % (75 students of 320) and

37 % (118 of 320) of registered students, which shows the high rate of students giving up in this topic from the beginning.

Figure 3 also shows the percentage of correct answers in the three groups: In general, it is high, which demonstrates the interest of the students who have taken part. In group B, the percentage is slightly higher than groups A and C; since 85 % of the students who have decided to complete the tests across the *Virtual Campus* of group B are not "new" students of this academic subject.

Figure 3 shows the percentage of students that did not attend the final exam, those who passed, and those who failed during the last six years. We observe that in the last academic courses, in which we have applied the *Vedya* tool, we have reduced by 14% the percentage of students giving up the course with respect to the previous course, and at the same time, we have increased by 12% the percentage of students that passed the exam. The percentage of students that failed the exam increased by 2% due to the rise of students attending the exam. Comparing with previous courses (2003 to 2004) the percentage of students that passed has increased between 8% (with respect to the course 2003/04) and 15% (with respect to the course 2002/03).

6 CONCLUSIONS

In this paper, we have described the usage of an innovative educational environment for the interactive learning of data structure and algorithmic schemes by means of the visualization tool called *Vedya* and the specification language *Maude* with its programming environment in the *Eclipse* system.

In the last years, many papers on visualization of data structures and algorithms have been written. For example, a tool with a similar style is presented in (Chen and Sobh, 2001). Nevertheless, there is a lack in many of them of a graphic user interface of data structures and algorithms or they can only be executed in a few operative systems. In this sense, *Vedya* is something more than a simple tool for the execution of data structure as has been shown in Section 2 and (Segura et al., 2008).

The application of *Vedya* and *Maude* in a complete system as *Eclipse* allows the students the possibility of acquiring the capacity of implementing, correctly and properly, a data structure according to its formal algebraic specification, using in their design, the proper algorithmic schemes. As a consequence, it is possible to provide the students with a complete and professional methodology of software development that is very useful in the current teaching of Computer Science.

During the academic courses 2006/07 and 2007/08, we have carried out a detailed study in classroom on the application of this innovative educational environment by the *Virtual Campus* of the Complutense University of Madrid, in the "Data Structure" and "Programming Methodology and Technology" courses corresponding to the second and third academic courses of Computer Science.

As future work, we plan to design an *Intelligent Tutoring System* in order to guide the interactive *self-learning* process of data structures from the algebraic specification to the real implementation.

ACKNOWLEDGEMENTS

This work has been partially supported by the Spanish National Projects FAST-STAMP (TIN2008-06622-C03-01), MERIT-FORMS (TIN2005-09027-C03-03) and PROMESAS-CAM (S-0505/TIC/0407).

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