Virtual Collaborative Experimentation: An Approach Combining Remote and Local Labs

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***Abstract*—The research presented in this paper shows how lab work can be organized into three phases: prelab, lab, and postlab, all supported by a Web-based experimental portal and a set of tools, some of which are connected to real lab devices. Different online tools and simulators are used in a flexible and configurable way that can be adapted to student curricula and course needs. This scenario is based upon real cases in distance learning courses in the Industrial Engineering School at the Universidad Nacional de Educación (The Spanish Open University), Madrid, Spain. The details of the combined real and simulated activities are discussed and some conclusions and lessons learned from this work are presented.**

***Index Terms*—Collaboration, distance learning, industrial engineering, learners community, remote experimentation, virtual chemistry laboratory.**

I. Introduction

LABORATORY work is an important part of education and is essential in engineering courses, where there is a pressing need for students to integrate their understanding of theory with laboratory practice throughout the academic year. As Colwell [1] noted "the role of practical work for learning science comes from the view of the importance of practical work introducing students to the world of scientists and engineers in practice."

In distance education, the physical separation of students who are in different geographical locations combined with the social problems that students may encounter as a result of not knowing each other, make the organization and implementation of effective experimental laboratory sessions difficult. Universidad Nacional de Educación (UNED), Madrid, Spain, organizes onsite lab sessions, which are concentrated in a block of two or three days both to limit travel obligations for the students and expense for the institution.

Given, however, that the students are strangers to each other, do not know how to work in groups, and are inexperienced in the practical challenges of laboratory analysis, the time available can prove inadequate to complete the assigned work. Some attempts have been made to help students with these difficulties by previously sending them documentation about the laboratory sessions, so that they can prepare in advance. However, due to the essentially passive nature of any preparation that they can undertake with these materials, the results of this have not been good.

A more promising solution to these difficulties is the application of Web-based experimental environments [2] that offer students the possibility of working in simulated environments, before actually coming to the laboratory. This preparation familiarizes them with the reasoning processes to be followed, so that, once in the laboratory, less time needs to be spent in understanding the nature of the experimental work to be done. Such online work can include a variety of activities, including the performance of experiments in either real or virtual settings, supported by a distributed collaborative computer environment. The premise of this approach is to offer a persistent, structured and dynamic workspace that sustains both their personal and their shared knowledge in a long-term learning process. In some circumstances it could be argued that such online simulated experimentation would itself be sufficient to give students an idea of the types of analysis that need to be undertaken. In the context of degree-level industrial engineering, however, real laboratory sessions are essential. Furthermore, the aim of this paper is to show that combining both virtual and real approaches, with an appropriate pedagogical approach, that includes both individual and collaborative work, is the most effective way to learn.

The research presented in this paper shows how experimental work can be organized into three phases: prelab, lab, and postlab, all supported by a Web-based experimentation portal and a set of tools, some of which are connected to real lab devices. This approach enables students to perform lab work with colleagues, which is both more motivating than doing it alone, and also enables students learn to collaborate. A student is given the opportunity to perform experiments at home, in collaboration with a peer, without any time pressure. This way of working enables students to reflect, and to relate theory to practice, which is not possible in the lab because of time constraints. Furthermore, in this preparatory phase, the focus is on the development of critical reasoning skills in an experimental context, such as formulating hypotheses, analyzing experimental results, and using these results to formulate further experiments. Finally, students should be able, in collaboration, to explain their results, and justify these explanations. These skills are fostered through a carefully designed collaborative activity sequence. In general, a Web-based experimental lab is effective in enabling students to prepare lab work, and is an opportunity for the teacher to prepare motivating and exciting activities for his/her students.

Today virtual labs are essentially *collaboratories* [3], [4]. These model different scientific activities, offer a common

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1. Atoms and elements
2. Periodic table
3. Chemistry Thermodynamics
4. Types of Chemical Bonds. Ionic bonds
5. Covalent bond and Lewis structures
6. Molecular structure.
7. Other types of bonds
8. Gas state
9. Liquids and solids. Changes of states
10. Dilutions. Properties of the dilutions
11. Introduction to organic and inorganic chemistry
12. Kinetic Chemistry
13. General principles of the chemistry balance
14. Thermodynamics and chemistry balance

Fig. 1. Syllabus of the course "Principles of Chemistry."

workplace for learning and provide support for sharing and using different remote devices related to different scientific disciplines, such as physics [5], chemistry [6], [7], astrophysics [8], medicine [9], and engineering [10]–[12]. Many of these projects take great care to design motivating activities for the students and offer rich and easy-to-use interfaces which reproduce the physical interface of the devices to which they are connected. The main objective of these systems is the substitution of the physical lab by a collaboratory. The Active Document approach presented in this paper does not attempt to present virtual laboratories as a substitute for conventional ones, but should be considered a preparatory phase. In this preparatory phase students are given the opportunity to acquire part of the reasoning skills and knowledge that they will then combine with practical experiment design and performance in actual lab sessions.

This work is the result of several years of research and testing within a community formed by students and teachers. The subject area of the experiments is functional analysis in organic chemistry. The targeted students are distance learners: industrial engineers in the first and second year of their university studies, in a distributed community of tutors and students with lab premises in different local study centers in many different parts of Spain. The Web-based environment is a computational architecture that enables collaborative learning activities, remote experimentation and server-access with remote devices in a central lab.

In Section II, the structure of the chemical laboratory scenario is discussed, followed by an overview of the pedagogical aspects of the online activities. The details of the combined real and simulated activities are then discussed, and some conclusions and lessons learned from this work are presented.

II. Organic Chemistry in Industrial Engineering Studies

This scenario is based upon real cases in distance learning studies from the Industrial Engineering School at the UNED. Chemistry is one of the basic subjects, and it is studied in the first two years: "Principles of Chemistry" (first year, see the syllabus in Fig. 1) and "Fundamentals of Engineering Chemistry" (second year). The first of these courses involves many students with laboratories being geographically distributed throughout the study centers, and lab experimentation is highly organized. Students have to go to their nearest center for two days to work in the lab (usually in March) and are organized in groups of two, with a maximum of ten groups per session. This practical work is obligatory, and has to be carried out only once. There are different tutors for the different sessions. Lecturers in the Engineering School establish the guidelines, but tutors define the actual deployment and organization of the experimental work in each center. The experiment described in this work corresponds to the practical work for lesson 11 in this subject (Fig. 1).

A. Experimental Description

The problem students are required to solve is that of identifying the elements present in a sample of an organic substance. The experimental method used is: *Elemental analysis and functional organic grouping*, consisting of four main phases.

1) *Production of an Alkaline Fusion.* Students have to make observations (visual and olfactory) of the physical and organoleptic properties of the unknown compound. Then, they have to perform different procedures to obtain a solution from the compound sample. The result of these tests is called an *alkaline fusion*. This procedure transforms the original component into an ionic solution of the elements, from which state the elements can be analyzed.
2) *Identification of Elements.* Subsequently, three kinds of different sets of tests are performed on the alkaline fusion, to identify the presence of N, S, and halogens (X). These tests depend on the substance to be analyzed and in each case there is more than one way to detect an element.
3) *Inferring the Functional Group.* Based upon the relation between solubility and structure there is a well-known classification table with seven different groups. In each group there are different functional groups. The first step is to establish which group the unknown sample belongs to. Then, identify the functional group by further investigation. Each step consists of performing a test, observing the results (clarity and color of the solution) and drawing conclusions from the previously obtained data. Once the group is determined, chemical tests are used to identify the functional group. This phase involves a chain of reasoning from evidence to inference, i.e., students have to formulate a logical claim according to the given evidence.
4) *Confirmation of the Functional Group Identity.* For this task, students have to compare their hypothesis with the infrared spectrum of the inferred functional group. The infrared spectrum is given to them on a sheet of paper. They have to check their hypothesis, selecting the appropriate intervals on the signal, and finally they have to provide an interpretation for the main bands of the spectrum.

As a conclusion to the experiment they have to write a report with the following structure: functional analysis; physical observation; state, color, and smell; element analysis; solubility; classification tests; reactions, observations, deductions; and interpretation of the infrared spectrum.

B. Development of the Online Scenario

The first step was to analyze the current practice through observation of a series of student lab sessions throughout an academic year, together with subsequent in-depth discussions with the teaching staff. As a result, several major problems were identified. First, although students were provided with documentation for the lab work in advance, they typically did not work with or even look at the guidelines before coming to the sessions. Second, the tight schedule of the lab sessions does not favor thinking and reflection. As students had no previous experience of lab work, they needed to focus on figuring out what to do, by making decisions as they went along, and carrying out procedures outlined in the guidelines, is much the same way as they would if they were following a recipe. The result was a very poor application of their theoretical knowledge.

Experiments were performed in groups of two. Students had no previous experience either of collaboration or collaborative support for the work they had to perform together in the lab. For instance, each student used personal notepads to write observations and annotated their own copy of the guidelines during the lab period. Often they did not check whether their notes were complete, complementary or indeed consistent. These sketchy notes were used subsequently, but usually the final report was an individually-written document prepared from scratch.

To address with these problems, and given that lab schedules cannot be changed for organizational reasons at the institutional level, the inclusion of a prelab period was proposed where students, in their own homes and at their own pace, could carry out virtual lab activities in a collaborative way. Then, to help them to reflect on the lab activities, a collaborative postlab was also proposed.

C. Implementation of the Online Scenario

The approach adopted here has its origin in a standard face-to-face laboratory setting. The goal was to improve the process, taking a very realistic and learner-centered perspective. Subsequently, a pilot lab course in organic chemistry was created, using a scalable model that takes into account the constraints of the social context in which this work is taking place. Then, after a formative evaluation, the prototype was improved to solve the problems observed and to respond to the teachers', students', and tutors' comments.

III. Pedagogical Motivation

The approach used in this work combines individual and collaborative learning in remote and local laboratories, in a distance learning context, and proposes the use of a Web-based experimental environment to improve the development of reasoning skills in practical work.

A. Experimental Learning, E-Learning and Distance Learning

Experimental learning is particularly difficult because students have to undertake work where the processes they have to understand and follow differ for the theory they have previously learnt [1].

Networked technologies open the way to the creation of new lab frameworks for science education in a distance-learning context. They offer users the opportunity to put into practice previously learnt theoretical knowledge, independently of the geographical location in which a student finds him/herself. The availability of these technologies opens up a wide spectrum of possibilities for designing and engineering new teaching methods that can make the most of these situations. While actually working in a real laboratory still remains crucial, combining this approach with virtual lab work is argued to be of great importance in strengthening and fostering the learning process.

B. Collaborative Problem Solving

Group work is fundamental to laboratory situations, either real or virtual. Furthermore, from a pedagogical point of view, it is important that students are able to coordinate their activities, and reflect jointly on what they have done in the lab. Technology can be used in virtual activities to facilitate both communication and collaboration and allows both the creation of and support for learning communities [13]. Characterized in terms of social construction of knowledge [14], these learning communities are featured in various learning theories, such as Constructivism [15], Activity Theory [16], [17], Distributed Cognition [18], and Situated Learning [19].

The technology associated with a large range of interactive and collaborative tools has become affordable for a wide spectrum of the educational community, opening up the possibility of supporting social constructivist learning approaches undertaken in computer-based environments. The creation of a custom learning environment, however, is still very time-consuming. The complete coverage of a single subject area would require a considerable amount of effort. Therefore, the current trend (as in the system presented here) is to design systems where the activities that the students have to undertake can be specified independently of the subject area. Such learning designs also allow different forms of collaboration and ways of sharing data and scenarios. It is possible to track how the students work with the system, and to store the results of all the activities undertaken [20]. Students can be monitored either manually by the teacher or automatically, enabling extra help to be provided to the students as necessary [21].

Chemistry lab activities could be seen as problem-solving tasks with multiple possible paths depending on the intermediate results of the experiments. Performing these in groups converts the lab work into a collaborative problem-solving activity, during which the student often has to rationalize why he or she made a particular choice [22]. These rationalizations make explicit the strategic knowledge that would otherwise be implicit.

IV. The Web-Based Collaborative Learning Environment

A. The General Architecture

The Active Document (AD) system [23] developed here for these virtual laboratory scenarios is a Web-based collaborative learning environment used to organize and invoke the different tools that make up the chemistry virtual lab. The interface is a portal where the user works with concepts in projects, obtaining data, and manipulating artifacts. These artifacts are usually models of ways to solve a problem, created previously by students in different groups, which are stored and then shared by the larger learner community.

The AD system is a computational architecture for eLearning that allows collaborative learning activities to be undertaken by

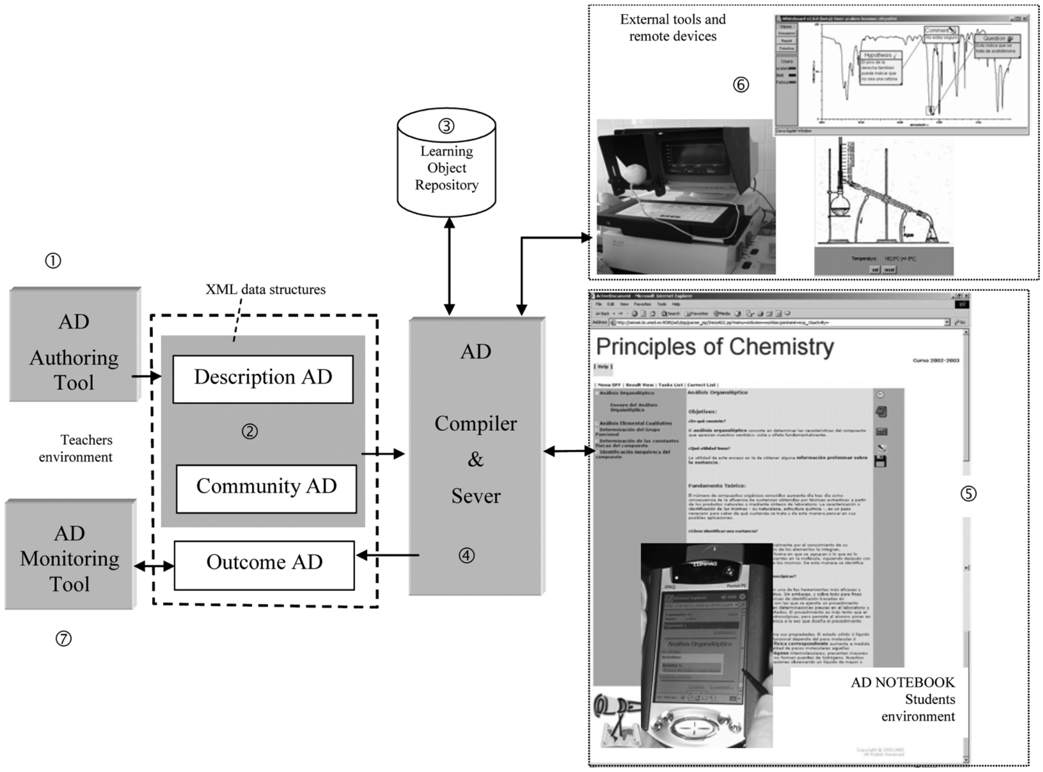


Fig. 2. The Active Document general architecture.

means of use of a variety of resources shown in Fig. 2. The system is composed of a set of authoring tools (labeled ①) for the creation and configuration of the different AD files (②) required to specify of the learning activities; a repository of distributed learning objects (③) consisting of a variety of tools and resources for the described activities; a compiler (④) which generates the user environment necessary to carry out the described activities (⑤), together with the AD server and the appropriate resources and tools (⑥); and finally a set of monitoring tools (⑦) assesses the group's performance and provides feedback.

B. Learning Object Repository

The central medium for sharing and exchanging students' artifacts is the learning object repository (LOR) [24], which is the persistence mechanism used by the system to allow users to share and reuse their results between tools. Such persistence is necessary so that a student can both store their work in the three different phases of the practical work and also reuse previous results as they progress from one phase to the next.

C. The Active Document Authoring Tool

Students gain access to the collaboratory through the Active Document Notebook which is generated by the AD System compiler. The AD Authoring Tool allows different ADs (required for specifying the learning activities) to be created and configured. The authoring tools are currently extensible markup language (XML)-based editors which allow a lecturer to compose a set of ADs for specific learning applications. Two files are needed to define an AD Notebook. First, the description of the division of labor in the tasks and subtasks (referred to as ② the "Description AD" in Fig. 2). Second, the actors and roles involved in the collaborative tasks (referred to as the "Community AD" in Fig. 2). Furthermore, the teacher can also configure the structure of the outcome of the activity (referred to as the "Outcome AD" in Fig. 2). Underlying system data and student results are stored in XML, with the appropriate associated metadata, so that they can be used flexibly.

D. Support for Remote Experimentation and Collaboration: the Active Document Notebook

The laboratory scenario is described in a "Description AD" file which includes information on what tasks the students will undertake, which tools they will use, and what other resources they will have available. Different tools are also available to enable students to communicate both synchronously and asynchronously. This support will be described in detail in Section V below.

E. Teacher Support and Lab Monitoring

In distance education, students should receive feedback from the teacher throughout the learning process, particularly in practical and laboratory-based activities. In Web-based activities this feedback is particularly important since the student can easily get lost or become demotivated. Therefore, the system described here includes an explicit mechanism enabling teachers to follow student progress and to provide the necessary advice and guidance. This monitoring is done manually, using the AD Monitoring Tool which organizes and presents the group activities in such a way as to facilitate the learning process. Hence, a teacher can understand "at a glance," the situation in which students

TABLE I
ORGANIZATIONAL MODEL FOR THE VIRTUAL COLLABORATIVE SCENARIO

PHASE	LEARNING GOAL	EXPERIENCE TYPE	AIM	ACTIVITY TYPE	COM. TYPE	INPUT	OUTPUT
pre-lab	Learning by exploring	Virtual Simulated	Improve student background knowledge, reasoning skills. Understanding of the experimental process Improve student collaboration	Collaborative Problem Solving Collaborative inquiry (gather, analyze and interpret data, justify)	Asynchronous	substance X	Partial results for X (identify elements, functional group)
lab	Learning by doing	Real	Develop student ability in planning and performing experiments	Collaborative Problem Solving Real lab performance (develop and apply scientific skills)	Synchronous	Substance Y	Partial results for Y (identify. elements, functional group)
post-lab	Learning by reflecting	Virtual	Encourage students to reflect on the experimental process, and to develop abstract concepts	Collaborative writing, Collaborative scientific reporting	Asynchronous	Partial results Pre-lab and lab phases, Report Schema	Report

find themselves, and can provide the relevant help and feedback, depending upon the cognitive and collaborative needs of the individual.

V. SCENARIO DESCRIPTION

As stated above (Table I), three phases are considered necessary for this process. For each phase, a computer-supported environment offers a structured scenario with the functionality to support individual and collaborative activities. This way of organizing students' activities can be seen as an example of collaborative scripts [25] for Web-based experimental learning which organize laboratory work by combining local and remote experimentation. The script's three-stage structure provides students with the necessary guidance to acquire scientific knowledge. Prelab and postlab work was carried out at a distance and the lab phase took place in the laboratory. Data from one stage was stored in the repository and was available for the next stage. During the prelab and the postlab phases students could freely decide whether to collaborate with their colleagues or not and either to report their results individually or as part of a group.

During the prelab phase students worked at home carrying out problem-solving activities organized into several tasks (exploring possibilities, selecting a substance, performing a simulation, interpreting data) in order to develop an understanding of the subject matter and to acquire collaborative inquiry skills. The collaborative activity involves solving the *Elemental analysis and functional organic grouping* (described in Section II-A) in groups, as a collaborative problem. Each decision must be taken as the result of a discussion process, and when agreement has been reached the group can progress to the next step. All decisions must be explained.

In the lab, students work in pairs in a real laboratory and focus on the manipulation of chemical tools and chemical processes; the system supports data collection as well as some collaborative modeling in this phase. In the postlab, students use the system from home, collaboratively, to reflect upon and discuss in depth the theoretical background and the experimental work carried out the lab.

The goal of the prelab phase is twofold, mirroring the way in which scientific knowledge is acquired in collaborative efforts. First, to improve student background knowledge, using a problem-solving approach. Students are asked to solve cases similar to those in the real lab, but here the physical and chemical manipulations to obtain data are simulated. In this prelab phase the emphasis is on acquiring particular critical reasoning skills. Second, to enable students to work in collaboration, developing abilities such as being able to choose an approach, argue their opinions, and construct or justify a particular explanation.

This environment enables students to undergo a "simulated" lab experience. An experiment is presented as a space of related tasks where the virtual environment includes all the possible steps or paths that could be followed during the experiment. Students have to explore the task space and decide which subtask has to be performed next for a particular problem-solving situation, based on the evidence accumulated so far. A number of software tools, including discussion facilities, are provided for this purpose.

In the lab phase a personal digital assistant (PDA) is available to each student group. The support environment is the same as in the prelab phase, but with enriched contents and functionality, for instance providing help on how to do a particular manipulation. This assistance could also be in the form of animations. Students work together in the same physical location. Data collected on the experiments may be either images or texts from the intermediate processes or from the final outcome.

In the postlab phase, students in their own home jointly prepare their final laboratory reports, again using the virtual environment. These reports should include detailed explanations that consider alternative approaches and solutions, as learnt in the prelab phase. This task is designed to be a collaborative writing activity.

Teachers are able to correct and comment upon these reports as soon as students publish them online. Students are kept informed of the status of this correction process, and can see the comments as soon as the report has been corrected.

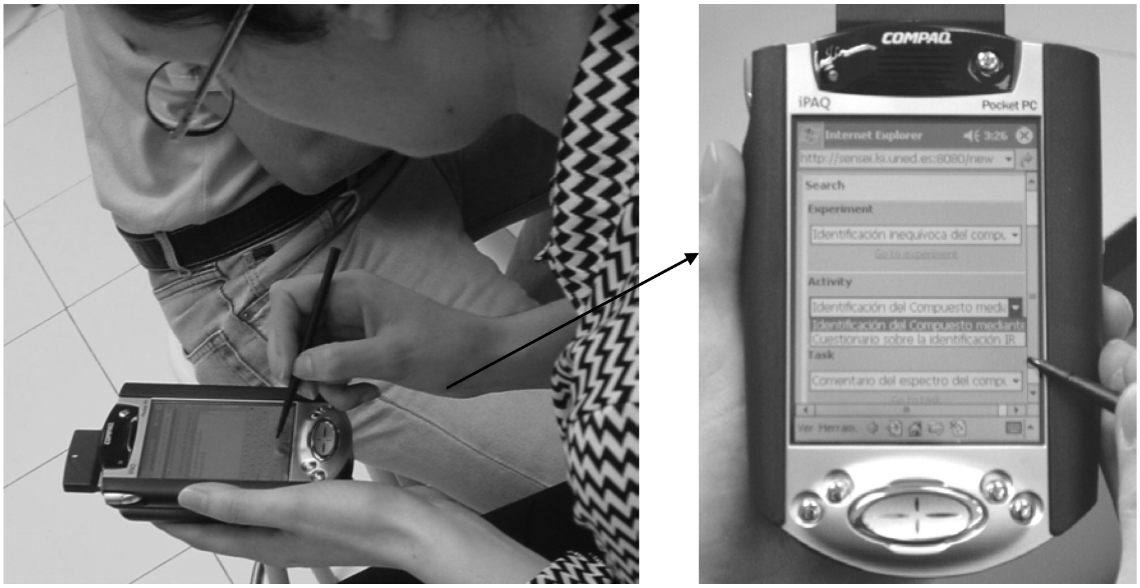


Fig. 3. The lab phase.

VI. Scenario Implementation

This scenario includes real lab experimentation using a basic chemical kit and handheld computers, connected wirelessly to the AD server, as well as distance learning activities, at home, with a mix of virtual and remote experimentation.

A variety of support tools are available, some for the whole scenario period such as structured glossaries, others specifically intended for a particular phase, such as simulation models.

A. The Prelab Phase (virtual Lab and Remote Manipulation)

The experiment is organized into activities where each activity consists of a set of possible tasks, to be carried out either individually or collaboratively. Tasks are defined in the description AD, and can be changed. In this phase, tests are performed virtually, through simulations. In contrast to the real lab, where for reasons of safety and of economy certain potentially harmful or expensive tests are not allowed, in the virtual lab students can explore what happens with a range of different tests, creating an opportunity for discussion with their peers on what to do next and why. Students start by solving a simple problem, in order to become familiar with the environment, and then work in pairs on a more complicated task.

To tackle a problem, students have to adopt a search strategy in the task space. For each task, students have to: 1) discuss in between themselves, and take a decision as to whether to proceed or not, justifying their choice; and 2) explicitly identify their initial hypothesis and explain the data they collected and the conclusions reached. In this prelab phase students obtain data either by running a simulation, or by querying a multimedia database.

The final task to be performed is the analysis of an infrared spectrum to check whether the analytical inferences match the infrared results. To obtain the spectrum, students have two options: either they search for it in a database, or they create their own infrared spectrum by analyzing a sample of the substance in real time and remotely manipulating the infrared spectrograph. The use of a professional tool helps the student to relate his/her work to the real-world context. Access to the remote device has to be reserved in advance, because the samples to be analyzed have to be manually placed in the device, and, thus, only one group can perform this test at a time. Typically there are six different samples available, and each day of the week a different one is available during the prelab period.

The last step is to create a common interpretation of the data, by means of a graphical collaborative annotation tool that allows students collaboratively to annotate the spectrum. All the resources needed by the students are made available by the AD portal, which integrates a variety of tools including remote access to the infrared device.

The environment described here is generic in the sense that it provides an example of learning activities which tasks are carried out in a structured problem-solving space. Learning is viewed as a collaborative exploration driven by discussions.

During this phase, the role of the LOR is as intermediate data storage which treats partial results as learning objects (automatically labeled with contextual metadata). These student constructions can be consulted or reused in the next following phases.

B. Lab Phase

In the lab phase, students work together in small groups using an interactive online environment integrated with the physical laboratory system: the lab activity is the same as in the prelab but with different chemical substances. Appropriate experimental procedures and tools have to be selected, results obtained, and finally, a conclusion has to be drawn based upon the accumulated evidence. Due to the nature of a chemistry laboratory, where the presence of standard desktop PCs among the chemicals is somewhat impractical, the students use PDAs running on specially developed client software, connected to the platform via a real time synchronous wireless link (see Fig. 3). The environment accepts a variety of inputs, for instance, photos taken by

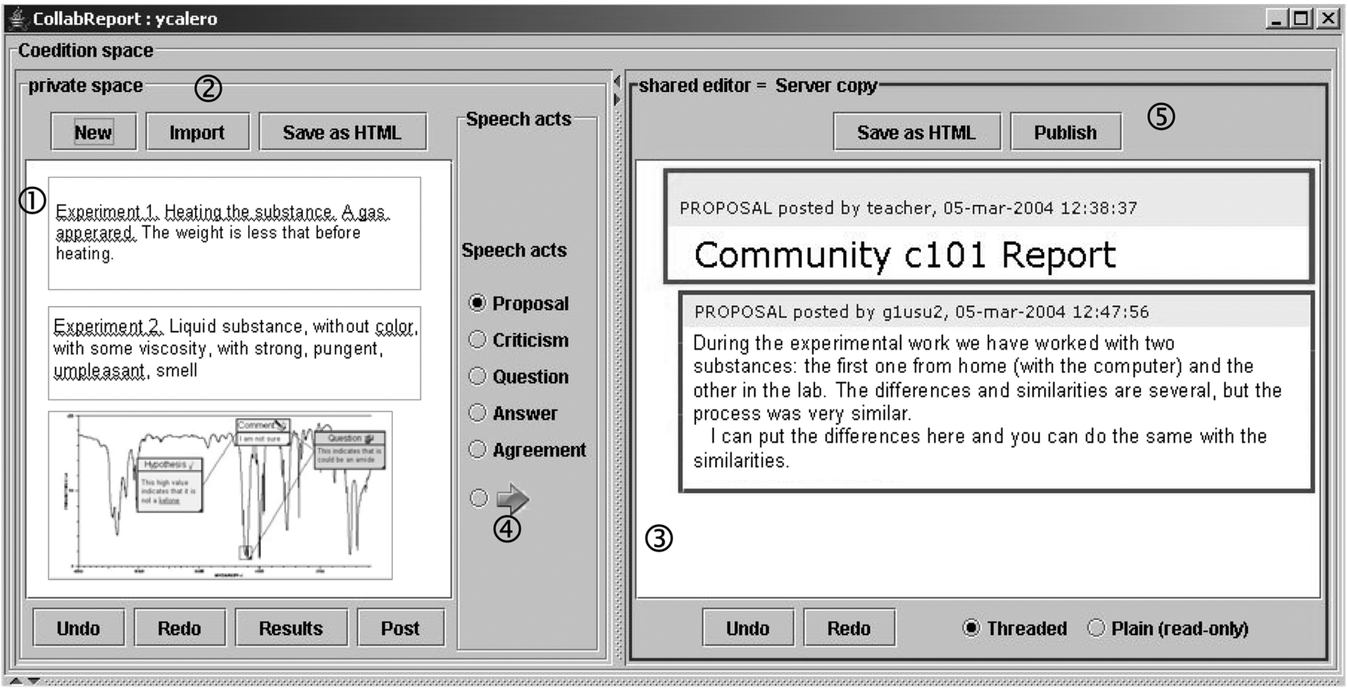


Fig. 4. Collaborative reporting task in the postlab phase.

the students, and offers different functionalities, such as annotation of the results obtained in the lab. All such data is stored in the repository together with metadata that enables them to be both contextualized and subsequently retrieved.

C. Postlab Phase

Once the experiment is completed, and the students leave the laboratory, the postlab phase begins, which is essentially a collaborative writing activity, undertaken from the students' homes, using any desktop PC with a standard Web browser to connect to the AD system. Students have to write a group report and submit it to the teacher for correction online.

The pedagogical goal of the collaborative reporting task is to encourage students to reflect on the results of the previous stages. The collaborative reporting tool interface is shown in Fig. 4. The left-hand part is an individual work area (labeled 1) where each student can upload objects (extracted from the LOR, using the "Import" button, labeled 2). For instance in this snapshot, the collaboratively annotated infrared spectrum has been uploaded. The right-hand side is the common group work area (labeled 3), which has sections that help to structure the reporting task. Students work together to create a final report, where they can move and integrate the available objects selected from the LOR (using the arrow labeled 4) on the left-hand side, to their report on the right side. Students submit the final report to the AD environment using the "Publish" button (labeled 5) and this document is evaluated by the teacher using the AD Monitoring tool.

D. Monitoring During the Prelab and Postlab Phase

During the prelab phase, monitoring is carried out in two ways. First, there is an overview of the student activity, the group members and the actions that the teacher has planned for each one (View, Mark, Print, Send an e-mail), and the state of each one (Not started, New Work, Nothing new). Second, the various stages through which a student has passed are shown, which enables the teacher to see if the student is on the "right path." This process is domain dependant and the "right path" will depend on the substance that the student has to analyze, since each substance requires a different analytical process which will depend upon the results that the students obtain as they progress through the experiment. Furthermore, thanks to the virtual environment, a student can be given additional activities as he/she goes along, and even new group activities can be spontaneously generated.

In the postlab phase, the teacher can access the report of each group. He/she can read it and send comments about the progress of the work and, subsequently, assign a grade.

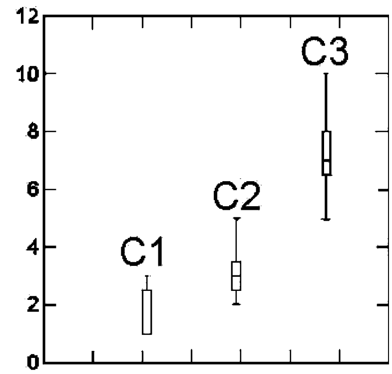
VII. Features Observed and Lessons Learned

The work presented in this paper is the result of several years' effort that has enabled different types of evaluation to be performed and different prototypes to be built. There have been three prototypes: the first one focused on the prelab phase, and was used by 12 students. The second one included the actual laboratory session, and was used by 52 students, and finally, the third one covered all three phases and was used by 48 students. The third prototype is analyzed here because it covers all three phases and is, therefore, more illustrative. This system is obviously the most complete, both in terms of functionality and stability.

Only 31 of the 48 students who took this subject completed the year. These 31 students were the basis of this study. The other 17 students dropped the subject (i.e., did not even start the practical work; or did not complete the final exam), a number consistent with attrition rates seen in Distance Education learning.

	SAMPLE SIZE	MEAN	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
CATEGORY 3	8	7,250	1,488	±1,24
CATEGORY 2	12	3,083	1,188	±0,75
CATEGORY 1	11	1,727	0,905	±0,60

(a)



(b)

Fig. 5. Statistical summary of experimental analysis. (a) Table diagram. (b) Box diagram.

Students were classified into three groups: Category-1 (C1) represents students who worked individually; that is, they did not try to communicate with their colleagues and sent an individual report. Category-2 (C2) represents students who exhibited a low degree of collaboration, i.e., those who presented a joint report, and exchanged some e-mails. Typically collaboration and communication between the group members is very low, leading to uncoordinated activity. Students are used to working individually, and while they all appreciate feedback from tutors, some are reluctant to work with peers. Initially, students with this profile would benefit from a more collaborative strategy. Category 3 (C3) considers students who successfully managed to coordinate their activities, and submitted a collaborative-written report. This data was gathered by the system, using logs.

Each student received a final mark between 0 and 10. This evaluation was performed by the teacher in charge of the subject area and was totally independent of the team creating the virtual the collaborative system. Using the monitor tool, the teacher evaluated the final report written by the students. She graded their work and this grade could be seen by the students. Sometimes they had a subsequent opportunity to improve their report. The average mark and the standard deviation for each category are shown in Fig. 5, using a table [Fig. 5(a)] and a box diagram [Fig. 5(b)].

Statistically, applying the classical t-test, students of the "collaborative" C3 group obtained higher marks than the "little collaboration" group C2, $(p \ll 0.001)$ which in turn was better than the "individual" group C1 $(p \ll 0.001)$. Hence, even a limited degree of collaboration significantly increases performance

The evaluation shows that the student who undertakes the prelab work achieves better results in the laboratory, which to a large extent is a predictable outcome. In this case the student is in fact doing the work twice: first, in simulation, and second, in reality. Finally, the postlab enables the students to reflect upon the work they have done and to consolidate what they have learned.

VIII. CONCLUSION

The creation of a collaboratory typically requires access to remote devices and common workspaces, where scientific knowledge is "constructed and shared" between the students, allowing them to relate theory to practice. Students in such a scenario are also provided with opportunities to carry out activities that enable them to reflect on the activities they have carried out, which enables them better to understand the work they have done. In order to achieve these objectives, both an appropriate technological model and a well-designed, relevant set of activities which directly support learning are necessary. The practical work must also be organized, which in itself requires an additional effort on the part of the teachers. In this paper, the authors' experience of applying the AD System to Chemical Engineering laboratory courses over a period of several years has been presented. The results of this work have shown that the addition of virtual laboratory scenarios which include simulations, collaborative tasks, and periods to encourage student reflection, greatly improved the learning of the experimental material and enabled students to work more effectively when they actually undertook the real lab work.

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