The Essential Role of Language Mastering in Science and Technology Education

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Abstract— Education is based on mutual communication between the teacher and the learner. Any other process leading to acquisition of knowledge is based on communication between a certain source (a person, a book, other types of sources) and the person who aims at acquiring knowledge. The quality of the communication determines the quality and efficiency of the learning process and the quality, depth and completeness of the acquisition of knowledge – where by *acquisition of knowledge* is meant not a passive ability to reproduce memorized materials, but the sort of internalization that makes the learner capable of developing independent ways of reflecting and thinking on the material concerned. Language is the fundamental tool for communication, and has a fundamental role also in the development of abilities in other communication tools like visualization or the use of symbols. Language is also the fundamental tool for the development of thought and is, therefore, essential for all the inquiry aspects in the sciences and in the trains of thoughts leading from information to interpretation and ultimately to theory. The article: underlines and documents the importance of language mastering for students pursuing science or engineering careers; suggests that the development of language-mastering abilities, up to the sophistication levels needed for the generation and communication of scientific information, needs to become a relevant component of science and technology education; and discusses some possible implementation pathways.

Keywords—interactive teaching and learning options, language and logic, language of science, language mastering and science learning, teaching of logical relationships.

I. INTRODUCTION

Language is the fundamental tool for the development of thought [1] and, therefore, for any acquisition of knowledge by human beings (for the cognitive process [2]). It is thus an essential tool for all the inquiry aspects in the sciences (identifying investigation questions, identifying relationships between pieces of information, formulating and verifying hypotheses, making inferences) and in the trains of thoughts leading from information to interpretation and ultimately to theory. The relationships between language and knowledge have been the object of extensive philosophical investigation – an investigation that incorporates the issue of the very nature of scientific knowledge, as knowledge does not go beyond our expression of it (or, in other words, knowledge is identified by our expression of it). Even a quick overview of the main trends in the investigations and reflections on these aspects would go beyond the scope of the current work. However, the awareness of the importance of the intimate all-permeating connections between language and knowledge constitutes a necessary foundation for all the considerations on the role of language-mastering in the teaching and learning of science.

Language is also the fundamental tool for communication; it enables more detailed, complete and complex communication than any other communication tool and is also the essential instrument for developing familiarity with the other communication tools (e.g., with visualization or with the use of symbols). The teaching and learning process is based on mutual communication between the teacher and the learner. Thus, the teaching and learning of science depends on the level of students' language-mastering in terms of all its aspects and components: in terms of communication effectiveness, which is based on the understanding of the literal meaning of what is explained by the teacher or by sources like textbooks or other materials; in terms of the gradual acquisition of knowledge inherent in the learning process and implying reflecting on the content up to the point of coming to mentally "own" it (as implicit in the etymological meaning of *acquisition*); in terms of the development of the ability to build independent ways of thinking on the basis of the acquired knowledge, which is the key to innovation. The obvious inference is that science and engineering students need sufficiently sophisticated levels of language-mastering to be able to make use of all the potentialities of language in order to pursue and attain real familiarization with the main aspects of doing science and generating innovations.

The importance of language mastering for learners to be able to acquire knowledge is broadly reflected in science education research, through a number of key themes:

- The studies on the difficulties students encounter in approaching science textbooks [3], or in approaching the science discourse as a whole [4, 5], identifying inadequate familiarity with the language of science as a major cause;

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- The search for options to facilitate the approach to textbooks, and to science material in general, by explicitly considering the role of language in science learning [6–9] and offering guidance for students to familiarize with it;
- The recognition of the pedagogical value of writing to stimulate science understanding [10, 11]. Writing is a typically literature-type exercise, where the effort to find ways of expressing things becomes a route to conceptual reflections and clarifications.
- The recognition of the professional value of writing Teaching students how to write science or engineering texts, both in their mother tongue and in languages utilised for international communication, is viewed as a relevant part of their preparation for the requirements of professional activities in the modern context [12–15].
- The suggestion that the science teacher should simultaneously be a language teacher, in order to facilitate understanding and stimulate creative thinking [16]. By advocating the attention to language aspects as integral component of science teaching, such a suggestion is close to a paradigm shift in the way of viewing language within the science class.

The present work considers the risks to the future progress of science and technology development posed by the current fast deterioration of language mastering among the young generation, offers a quick overview of the fundamental requirements of the language of science, and suggests some pathways for the incorporation of what could be called "education in the language of science" into the teaching of science and engineering courses.

II. THE DECLINE OF LANGUAGE MASTERING: A THREAT TO FUTURE DEVELOPMENTS IN SCIENCE AND TECHNOLOGY

Up to one or two decades ago (depending on the context), it was generally taken for granted that students entering science or engineering faculties had already acquired sufficient language-mastering to be able to understand the literal meaning of sentences (on reading or listening) and to be able to adequately express their acquired knowledge (on writing or on oral assessment occasions). Only underprivileged second-language instruction contexts experienced the problems of inadequate mastering of the language that was the medium of instruction, generating learning and understanding difficulties and hampering the general acquisition of science literacy [17, 18]; the awareness of these consequences prompted the recognition that the shift to mother tongue instruction would be fundamental for development [19, 20] – an inference whose validity is continuously confirmed by the analysis of the difficulties encountered by science students [21–24].

However, recent years have witnessed a fast deterioration of the quality of language-mastering among the young generation, which can be ascribed to the combined impacts of several factors: the decreased attention (decreased extent and depth) in the theoretical study of the mother tongue at pre-university level; the continuous decrease in the average number and literary quality of the books that young people read, resulting in decreased familiarity with written expression and with complex sentences; and the dominant use of communication technologies for which short, grammatically and logically unconnected sentences are viewed as the most suitable options (also for cost saving purposes, e.g., on sending SMS). The weight of the latter factor has been increasing sharply in very recent years. The language-mastering deterioration hampers learning and understanding in all the fields of study. For instance, in Italy (a context where a broad humanities basis had been traditional since long, resulting in generally satisfactory language-mastering levels), the rectors of a number of universities have expressed concern about the poor language-mastering level of many incoming students in recent years, and have adopted or proposed measures like language tests aimed at early diagnose of students' language-related difficulties, or the establishment of language courses for incoming students. This (that students reaching university have not yet acquired adequate language skills and need to learn the basics of language and expression within the tertiary level of instruction) would have been unthinkable up to a couple of decades ago. The seriousness of the situation can be illustrated by data. For instance, in 2005, 44% students failed the Italian language test at the University of Venice (Ca' Foscari) and 25 % of the answers to questions simultaneously testing language and logical abilities was incorrect; the institution responded by organising a *Written Italian Service* (SIS) for students, including a 30 hours course aimed at "enabling students to learn the bases of Italian language up to attaining expression and writing abilities including complex discourses". Inadequacies in language-mastering abilities become particularly evident when students have to write a thesis at the end of their studies; then logic, and the rational organization of statements and information, surface as the major problems, up to the point of "producing the impression that those students have not yet learnt to reason" [25]. These last comments, from an interview to Dr. Andrea Macchi (a researcher at INFM, National Institute for the Physics of Matter, with the Department of Physics of the University of Pisa) highlight the main threat from inadequate language-mastering by science students – a threat to the development of new science thoughts in future years, because of the risk of inadequacies in the ability to utilise the essential thought-development instrument. Innovation requires creative thinking, and creative thinking relies on language mastering as its major tool.

Analogous threats concern the future development of engineering, as the search for new solutions – either to address new problems or to improve on the existing solutions for problems for which some solutions have already been designed – relies on creative thinking. The modelling ability to solve non-standard problems (problems that cannot be solved by routine application of common protocols or existing software, but require specific modelling before a technical solution is designed) requires the same ability to develop logical sets of thoughts as innovation in science, thus requiring language mastering as the instrument of thought. Furthermore, engineering has an implementation component (e.g., in the construction worksites) where the clarity and completeness of communication is essential for the work to be done without errors. This requires adequate language mastering by the engineer, to be able to communicate all the relevant information in a correct and understandable way (where *understandable* refers both to the individual operations and to their sequence and connections) and – although at a different level – adequate language mastering by those who implement the work. Incomplete understanding or misinterpretations by the latter may lead to errors; and errors in engineering implementation are dangerous, as they may result in malfunctioning items with a variety of risks, including the risk of accidents. The importance of clear and complete communication (with zero "transmission errors") is greater between the design level and the intermediate operational levels, where intermediate cadres have to organize and supervise the work of others (at the more basic implementation levels, instructions are simple and directly operational, and are increasingly given through simple images).

Trying and designing measures to effectively address the problems ensuing from the fast deterioration of students' language-mastering abilities, so as to pursue the needed improvement in these abilities through pre-university and into the university levels, requires:

- Preliminary deep reflections on the nature and roles of language in the sciences, integrating the points of view of scientific knowledge and the pedagogical points of view;
- The exploration of approaches to convince students of the importance of paying adequate attention to language, so that they accept to put efforts in developing language mastering skills. This also needs to counteract the still diffuse misconceptions that language pertains to the humanities domain and is not so important for persons pursuing science or engineering careers.
- The exploration of options aimed at optimizing the combination of traditional (book-based) and modern technology (computer-based) approaches, to better stimulate students' attention and to combine the benefits of both options.

The following sections are devoted to reflections on these issues, on the basis of the working assumption that science education needs to take up the training in the use of the *language of science* and to design its specific approaches. There have been debates (e.g., at some tertiary institutions in South Africa) about whether the *language of science* education should be assigned to the humanities domain or to the science domain. Although the ideal option would imply an integrated approach between the two domains [26], it is here considered that, when such integration does not prove realistic, the task should be assigned to the science domain, because the depth and inextricability of the connections between conceptual and language aspects requires adequate knowledge of the science content to discuss the modes of expressing it and the conceptual errors that stem from incorrect use of the language. This would also have the additional advantage of convincing students that the language issue is really important in the preparation of a scientist or an engineer, as they witness that it is dealt with within the science or engineering faculty.

III. SOME INSIGHTS INTO THE LANGUAGE OF SCIENCE

The term *language of science* is here utilised to denote the mode of expression that is typical of the sciences. Its major characteristics can be summarized as being rigorous and being clear. The requirement of being rigorous responds to inherent correctness and to communication correctness. The *correctness* reference is provided by the characteristics of the object or phenomenon that is being described, and also by the way or extent to which we may know such characteristics; in other words, it relates both to the characteristics of physical reality and to important features of the scientific method. The requirement of *being clear* responds to communication effectiveness, and has *being rigorous* as its essential prerequisite [27, 28], as communication cannot be clear if it contains imprecisions or errors. These requirements are complied with through accurate selection of individual words and of the way of combining them to build clauses and sentences.

It is particularly important to recall the essential role of common words in building meaningful statements in science communication [27–29]. Each science has its own terminology – the ensemble of names denoting the objects and phenomena that it investigates. These constitute the technical terms of the given science, but they should not be confused with the l*anguage of science*, which is a complete mode of expression, conveying information. Within information-conveying statements, technical terms are embedded in a structure made of common words – the nouns, verbs, adjectives, prepositions, logical connectives, etc. that constitute the communication backbone ensuring the transmission of a meaning. For instance, in the sentence «*The presence of the* solute *lowers the* chemical potential *of the* solvent», the words in italics pertain to common language; they are also the words that link the technical terms (solute, chemical potential, solvent) building and conveying the desired piece of information. Thus, the roles of common words and sentence structures make adequate language-mastering an essential condition to understand and to express science:

- On reading or listening, it is necessary to understand the meaning conveyed by a text or a discourse fully, i.e., both the literal meaning and all the implications stemming from it;
- On speaking or writing, it is necessary to select individual words correctly and to associate them into sentences conveying meanings that are consistent with the characteristics of the object or phenomenon considered, as we know them.

Both aspects are fundamental in the teaching and learning process, as students need to be able to fully understand the meaning of what they read or listen to, and they need to be able to express their acquired knowledge in a correct and understandable way, both for assessment purposes (tests, exams, oral assessment options) and for their future professional activities.

It may be important to attempt a deeper insight also into the issue of domains, in view of the tendency to ascribe language as pertaining only to the humanities domain and "having to do" only with it. The theory of language (grammar, syntax) has been developed within the humanities domain, leading to codifications which – although making allowance for the "living" nature of language, as something in continuous change and evolution – provide rules that ensure communication efficiency and interpretation uniqueness. By depending essentially on common language, the *language of science* utilizes the same sets of rules in order to communicate scientific and technological information. A major difference with other uses of language (e.g., in novel or drama writing) is that the uniqueness of interpretation (the fact that only one interpretation of a given text is possible) is a necessity (a *must*) in science communication. It is self-evident that, for instance, only one interpretation must be possible in instructions on how to build a bridge or a plant, but also in the statement of a law or in the individual components of a model and in the way they link to each other. This requirement actually increases the language-mastering demands in science and technology communication.

Currently spread circumstances show a continuous decrease in the level and efficacy of language education at pre-university level – a decrease in the intensity and depth with which grammar and syntax are introduced to young people, a decrease in the extent to which the importance of precision and clarity are stressed, and, above all, a decrease in the attention to the logical connections between the components of a complex discourse. This enormously decreases the impact of language education within its traditional areas (humanities-related courses), diminishing the amount and the quality of language-related competencies that students acquire. Under such circumstances, it becomes necessary that science and technology disciplines take up the leadership in advocating the importance of language education. For science and technology disciplines, ensuring an adequate level of language mastering by the young generation is a question of survival (it would be a question of survival also for humanities disciplines, but their awareness of it appears less sharply defined in the current transition stage, in which it is clear that language mastering is declining at a fast rate, but not all the impacts on other areas are yet clearly predicted or predictable).

The minimal objectives that science and technology disciplines need to pose can be summarised as follows:

- Ensuring that the degree of language mastering remains above the level needed to maintain the possibility of transmission of information. If the clarity and completeness of the transmission of information is jeopardized, even existing technological knowledge risks collapsing at implementation level;
- Maintaining open pathways for the acquisition of the highly sophisticated language-mastering levels that are necessary for the development of creative thinking in science and in engineering.

This task is unprecedented as, since humanities and sciences split some centuries ago, it had always been possible to rely on adequate language-mastering levels by students entering universities, in whichever field of studies. It is the first time that science and technology disciplines need to undertake language education as a survival necessity. Besides their expected immediate pedagogical value, the challenges inherent in this task may, in the long run, lead to novel trends of reflection on the relationships between knowledge and language.

IV. CONVINCING SCIENCE AND ENGINEEERING STUDENTS OF THE IMPORTANCE OF LANGUAGE MASTERING

From a pedagogical point of view, the main message to be conveyed to students in a sufficiently convincing way is that the correctness and understandability of science communication depend on how language is used and that, therefore, the language-mastering required for the sciences concerns first of all common language.

It is necessary to counteract the diffuse misconception that language is not so important in the sciences, which students often translate into the oversimplified statement that the teacher "should mark the science, not the language". The misconception is not found only among students, it is present also in other levels, including some decision-making levels. There are still contexts where students can be admitted to science faculties even if they have very poor grades in language-related skills in their secondary school records, on the assumption that language skills pertain to the humanities domain and not to the science domain and, therefore, they are important only for students registering for humanities degrees. As long as this misconception persists at higher levels, it is obviously difficult for students in those contexts to overcome it (the message conveyed would be different if, e.g., students admitted to science or engineering faculties and having poor language-skills records were requested to take a language-skills course as pre-requisite or condition for their admission). The interventions to try and counteract the misconception at higher levels (where it is still present) need to be based on the provision of extensive documentation accompanied by technically unquestionable analysis; their discussion would go beyond the scope of the present paper, which focuses on the pedagogical aspects and the design of pedagogical options; however, they can largely be based on thought-threads analogous to those that will be outlined here for pedagogical interventions, viewing them from the point of view of general issues like the relationships between language and knowledge and of practical issues like the obstacles posed by language-related difficulties to students' performance in all science and engineering fields.

Students need to be guided to realize that science-learning and language mastering cannot be separated, that understanding depends largely on language-mastering, and that incorrect language unavoidably results in incorrect science because the literal meaning of an incorrect sentence corresponds to incorrect science. In other words, only a good knowledge of the language utilised as medium enables correct conceptual understanding and correct usage of the *language of science*. The essential role of language mastering in enabling science understanding can be easily spotlighted through simple reading exercises, i.e., by asking students to read the parts of the textbooks relevant to the issue that is the object of lecture/explanation/discussion at a certain time and to explain their meaning sentence by sentence. These exercises often highlight the presence of enormous inadequacies, including the very absence of the idea that sentences can be analysed in order to understand their meaning. Students often resort to passive memorization in front of sentences whose meaning they do not understand, but this cannot be viewed as learning (passive memorization becomes practically the generalized option when language difficulties become so dominant that understanding remains practically beyond reach for most students [24]). An adequate number of such exercises is needed for students to attain (and mentally accept) the realization that the difficulties that they experience in identifying the science meaning in their books depend on inadequate language mastering and that, therefore, it is necessary to learn to master the language in order to be able to understand science.

The role of language mastering in expressing acquired knowledge is effectively illustrated by the analysis of students' errors in their written works (reports, tests etc.). The analysis clearly shows that the majority of errors relate to the use of common language. Errors may depend on inadequate knowledge of the language that a student is utilising, or on incorrect understanding, or on both. Because of the intimate relationships between language and concepts in the sciences, it is difficult to untangle the language component and the conceptual component in an error, or to ascribe them individual weights [30]; but it is also true that conceptual understanding is largely conditioned by the student's ability to understand the literal meaning of sentences and discourses, i.e., by his/her language mastering. Considerable numbers of illustrative examples from chemistry courses are included in [21–23, 27, 28] and, therefore, only few examples will be considered here. For instance, in the following incorrect answer «There are no intermolecular interactions between ideal gases», the error is likely to be ascribed simultaneously to inadequate attention to the distinction between the microscopic and the macroscopic levels of description in chemistry (the *gas* concept pertains to the macroscopic description, while *intermolecular interactions* pertain to the microscopic one), but also to the tendency to oversimplification in the mode of expression, typical of students with poor language mastering (writing *between ideal gases* instead of *between the molecules of an ideal gas*). Similarly, in the following incorrect answer «The entropy change of an ideal gas is always positive», language errors and overall language oversimplification (writing *of an ideal gas* in place of *when two ideal gases mix*, as was expressed in the question) result in ascribing to a system (the ideal gas) a quantity (the entropy change) that can only pertain to a process (in the given case, the mixing of gases).

Systematic studies have shown that poor language mastering is the major factor preventing students from grasping those distinctions that are fundamental for a statement to be correct (besides being fundamental for conceptual understanding):

- The distinction between systems and processes and between what can pertain to the description of a system and what can pertain to the description of a process [31];
- The distinction between statements and concepts with general validity, and information that refers to particular cases [32];
- The distinction between physical quantities and their changes, often affecting also the problem solving level (e.g., in thermodynamics) [33];
- The distinction between numbers and values, related to the distinction between the two operations of counting objects (e.g., the number of protons in an atom, expressed by the atomic number) and measuring physical quantities [34];
- The distinction between the macroscopic and the microscopic descriptions in chemistry [35, 36];
- The distinction between considering one entity (e.g., *a gas*) or more entities (e.g., *two gases*), [22].

Students need to be shown repeatedly how errors of this type result in incorrect science, to induce the awareness of the importance of language mastering for science learning.

V. DESIGNING PEDAGOGICAL OPTIONS

Two aspects are fundamental in the design of options aimed at enhancing students' language mastering and their familiarisation with the *language of science*: the general pedagogical choice and the design route. It is here considered that interactive approaches constitute the best choice for the former aspect, and a route making adequate allowance for continuous (practically iterative) optimization constitutes the best choice for the latter.

Interactive approaches are necessary to maximize the benefits of any option meant to attract students' attention to language aspects [30]. Most science students' would not devote specific attention to language-related aspects and to their conceptual implications, unless they are stimulated and guided to do so. Since, in most cases, they are also unaware of these aspects (because of lack of prior exposure or training, or because of the inadequacies of the language tools that they possess), the guidance needs first of all to attract the student's attention, and then guide him/her to the identification of all the important aspects. This is carried out more effectively within interactive options, as they enable step-to-step guidance and real time responses by the teacher to any new aspect that may appear during a given activity. Moreover, direct interactions constitute the optimal option to highlight the links between language aspects and conceptual aspects (attempting to highlight them in written materials, like the course handouts, would lead to a type of text that students usually avoid reading, and would miss the communication immediateness that is needed to *navigate* among the complexity of language-concept relationships).

The main components of a design route aimed at responding to real needs can be schematically summarized as follows:

a) Diagnoses: identification of the needs, i.e., identification of the details of students' difficulties, through accurate analysis of their written works and through systematic attention to the information detectable during classroom interactions.

b) Design: trying to address the identified difficulties from as broad a scope as possible, to increase the probability of responding not only to the diagnosed details, but also to other that might arise; trying to predict the degree of effectiveness of the approaches under design, in relation to the characteristics of the target groups of students (age, context, etc.) and of the science discipline concerned.
c) Verification and validation: accurate consideration of the feedback from students' responses; it provides indications about the efficacy of the designed approaches and may highlight details that had not been identified earlier.
d) Refining: utilising the information from students' responses to improve the design.

Steps (b), (c) and (d) are potentially iterative. They can be repeated as many times as needed (whenever suitable or necessary) with the role of optimization cycles enabling continuous enhancement of the quality and effectiveness of the approach, including adaptations to the changing characteristics of students' populations from year to year.

VI. OPTIONS UTILISING TRADITIONAL TOOLS

This section will not consider only possible options utilising traditional tools, but also what needs to be addressed, as the consideration of the tools and the consideration of what needs to be addressed are interdependent and intertwined. Because of the more general character of "what needs to be addressed", many of the considerations outlined in this section will constitute references also for the next sections.

The first fundamental tool is the systematic complying with the requirements of *being rigorous* by the teacher; it is based on the recognition of the pedagogical value of rigour [37, 38] and needs to be inherent in the teaching approach by its very nature. Always using rigorous modes of expression, on explaining and within any other classroom activities, is tantamount to maximising conceptual clarity and to simultaneously providing *de facto* training to correct language usage within the sciences. It is an all-permeating tool which acts – one could say – by default.

The other tools imply active interventions, like questions and discussions aimed at attracting students' attention to specific aspects. For aspects like the selection of individual words, the building of individual clauses and the building of complex sentences, the analysis of errors is of paramount importance to simultaneously stress language-related features and science-related features, highlighting their interdependence on a concrete basis. It is also an ideal tool for interactions, as it requires individual contributions to a cooperative search for answers [30, 39] (while the errors' authors remain anonymous to prevent any perception of uncomfort by students).

The discussion of the selection of individual words contributes to underline their roles and usages in science communication. It focuses on the reasons why a specific word is the correct one in a given specific context and it finds apt opportunities in the analysis of incorrect statements in students' writings. For instance, the discussion of a statement like "*The equations for real gases consist of the parameters which depend on the chemical nature of gas*" (a type of error that is frequent in underprivileged second-language contexts [22]), needs to focus on the usage of *consist* and on the differences between *consist* and *contain*, also drawing examples from more familiar everyday situations to better highlight the meanings and the differences of the two verbs.

The analysis of sentences is important to train students to grasp the correct conceptual meaning on reading or listening, and to become able to build sentences that convey the desired meaning. It is a type of analysis that, in recent years, is often no more performed routinely within pre-university language courses (although, e.g., humanities based areas like history or philosophy would be ideal for it, in view of the rigour requirements of history and of the enormous value of each individual term and each nuance in a philosophical discourse). The analysis can profitably utilise both statements in textbooks (above all those that students find difficult to understand), with major focus on understanding, i.e., grasping all the information that the sentence conveys, and incorrect statements in students' writings, where error analysis demands a different type of mental engagement, more directly focused on how to express things.

An example of a statement that students find particularly difficult to understand, but which is also particularly apt to underline the importance of sentence analysis, is the highly rigorous statement of the third law of thermodynamics in [40]: «If the entropy of any element in the state stable at $T = 0$ K is taken as zero, every substances has a positive entropy which at $T = 0$ K may become zero, and does become zero for all perfect crystalline substances, including compounds». Classroom experience shows that the major difficulty stems from the fact that the sentence starts with a hypothesis (assigning zero value to the entropy of elements at 0 K). Many students lack even a basic perception of the meaning of *hypothesis* and of the fact that the presence of a hypothesis implies the statement of some consequences, and they fail to identify the next pieces of information (the entropy of all substances, whether elements or compounds, is always positive; at 0 K, the entropy of a substance may be zero, and it is zero if the substance is in the state of a perfect crystal) as consequences of the initial hypothesis. An in-class interactive analysis of the sentence elucidating all the logical connections typically requires at least 20-30 minutes.

The analysis of complex sentences implies the identification and discussion of relationships between pieces of information, which are essential to the scientific discourse. It thus simultaneously involves the consideration of logic (logical relationships between different pieces of information and the overall logic of a discourse) and the consideration of language as the instrument of logic, in an inextricable language-logic binomial. It is first of all important to note that, while persons with inadequate language-mastering levels tend to organize all the pieces of information in a parataxis-based way, the relationships that have key roles in the scientific discourse often involve hypotaxis with different hierarchical levels. The familiarization with the logical connectives expressing these relationships becomes a key both to conceptual understanding and to correct expression; it simultaneously becomes a key to the familiarization with the scientific method. Selected fundamental relationships will be considered in the next paragraphs for illustration purposes.

The cause-effect relationship (*A occurs because B has occurred* or, alternatively, *the fact that B occurs causes A to occur*) is fundamental in the scientific approach, above all in the interpretation processes. The way of perceiving it may differ in a discovery moment and afterwards, when that discovery has become part of the acquired knowledge. For instance, now we normally state that electrolytic solutions conduct electric current *because* they contain charged particles dissolved; initially (when scientists came to the conclusion that electrolytic solutions contain charged particles dissolved) the cause-effect relationship was from the observation to the inference, i.e., from the effect (electrolytic solutions conduct electric current) to the cause (electrolytic solutions must contain charged particles dissolved). It is important that students learn to see the relationships in the two directions, from the cause to the effect and from the effect to the cause. Diagnoses about their difficulties (and, therefore, materials for interactive error analysis) are particularly easy from practical reports, e.g., when they list the causes that may determine accuracy-decrease during an experiment and often list causes that do not affect the accuracy; but they are frequent also in answers to questions of the type "Explain why ...." [41]. For instance, an incorrect answer like "Electrolytic cells involve redox reactions only *because* spontaneous reaction is not possible *because* the reaction takes place in a single vessel" (to the question "Explain why electrolytic cells can only involve redox reactions") incorporates two incorrect cause-effect identifications that are interesting for conceptual clarifications in terms of error analysis, guiding students to realize that the fact that a reaction takes place in one vessel does not imply that it is not spontaneous, and the fact that a reaction is not spontaneous does not imply that it should be redox.

Relationships containing hypotheses are extremely important in the sciences because of the fundamental role of the formulation of hypotheses in the scientific approach [42]). As mentioned previously, they are also perceived as particularly difficult by many students, who fail to understand the role of hypotheses and the difference between a hypothesis and the other types of statements (e.g., the statements expressed by principal clauses). It becomes important to familiarise students with all the possibilities, so as to acquaint them with fundamental tools of language that also play fundamental roles in the scientific approach. The different natures of hypothesis-containing statements can be schematically summarised as follows:

a) *If A occurs, then B also occurs* (deterministic).
b) *If A occurs, then B may occur* (possibility).
c) *If A occurs, then B may occur; it occurs if C also occurs* (possibility & increasing situation complexity).
d) *If A were true, then B would be true*. This formulation relates to impossibility, and can be complemented by information like "*but B proved no to bet true and, therefore, we infer that A cannot be true*".

They can be illustrated by examples from undergraduate sciences, like (respectively) the following ones:

a′) *If sodium comes in contact with water, it reacts very fast*.
b′) *If the pressure on a real gas increases, its compressibility factor may decrease within a sufficiently low pressure range* (this is something that does not happen always; it depends on the nature of the gas).
c′) *If the pressure on an ideal gas is doubled, the volume of the gas may be halved; it is halved if the temperature is kept constant during the process*.
d′) *If Thomson's model of the atom had been true, the α particles in Rutherford's experiment would have behaved all in the same way; since they did not behave all in the same way, it was necessary to conclude that Thomson's model could not respond to reality*.

Sentences like (c′) and (d′) constitute examples of complex sentences – the category of sentence that students find increasingly difficult to understand and even more difficult to build. However, the acknowledged (section II) importance of being able to handle complex sentences in order to be able to understand the scientific discourse recommends that students get adequate training, so that they can learn to handle them.

Simple everyday life situations that can be outlined through two-clause sentences can be utilized to provide initial illustrations of the logic of relationships between different pieces of information and of the implications of different modes of expressing them. For instance, the following statements:

e) *When it rains, I take the umbrella*.
f) *If it rains, I take the umbrella*.
g) *I take the umbrella because it rains*.

can be utilised both as illustration of hypotheses-consequence or condition-consequence relationships (e and f), or cause-effect relationships (g) and as introduction to the distinction between statements with general validity and statements referred to particular cases. Both (e) and (f) are general character statements (with (e) emphasizing the concept that *every time A happens, B also happens*), while (g) has a particular character, referring to the specific moment when the person is talking. It is more difficult to find suitable examples for error analysis utilizing students' errors, because too often students simply refrain from writing sentences containing hypotheses; therefore, the analysis of sentences containing hypotheses need to utilize sentences from the textbooks and other resource materials.

Many students find it difficult both to perceive and to correctly express the distinction between the general and the particular character of statements. Given the importance of such distinction in the sciences, it is necessary to offer adequate exposure for students to learn to identify the two categories. One-clause incorrect statements that are frequent in underprivileged second language contexts appear particularly apt for error analysis aimed at highlighting the distinction. For instance, the incorrect statement "*Enthalpy is the state function*" is apt to highlight grammar-concept relationships, as the use of the article *the* would imply that enthalpy is the only state function. The incorrect statement "*A spontaneous process is a free expansion*" may result from inadequate perception of how it differs from the correct "*A free expansion is a spontaneous process*": the comparison of the two statements in terms of subject and predicate (language point of view) and simultaneously in terms of general and particular (the free expansion being a particular case of spontaneous process) is apt to underline the connections between language, understanding of the general/particular distinction and science concepts. The analysis of grammatically simple cases like these can constitute a first step to stress the importance of the general/particular distinction and are aptly followed by the analysis of more complex sentences.

Besides the familiarization with complex sentences, it is important to foster familiarization with complex discourses. The analysis of the logic of a discourse may utilise different tools, according to the nature and complexity of the given discourse. When the complexity increases, the collaborative (within classroom interactions) construction of diagrams visualizing the logic of a discourse proves particularly useful: it requires collaborative and interactive reading of the text in order to identify the relevant pieces of information and their mutual relationships, and the diagram construction engages the students' attention in a form of expression (visualization) closely depending on his/her understanding of the text [43]. Besides facilitating understanding, the exercise stresses the importance of accurate attention to the mode of expression in a text, thus stressing the connections between language and concepts. Flow charts are selected as the most apt types of diagrams for language-related and logic-related analyses, because they enable the consideration of logical sequences and of relationship hierarchies (concept maps would not respond to the same objectives, because of their basically paratactic nature, for which all the pieces of information remain at the same hierarchical level and there is no differentiation in the nature of their relationships). It has however to be noted that the development of the ability to understand visualization (the student's visual literacy) largely depends on language-mastering [44]; when the language-mastering level is too poor to enable this development, attempts to use collaborative construction of diagrams – even simple, 4 o 5 boxes ones – show enormous efficacy drop.

Science textbooks can also include language exercises referred to the content of the given discipline. An experiment in this regard, with the inclusion of language exercises in a chemistry textbook [45], has met positive responses. The inclusion of exercises with science-related examples into grammar textbooks could be considered as an option to further stress the connections between language and science, and how grammar errors result in science error.

VII. OPTIONS USING NEW THECHNOLOGIES

New technologies have an undeniable attraction for the young generation, which makes them particularly apt to reinforce the messages given through books and classroom interactions. Their use would also convey the additional message that there are no discrepancies between "traditional" and "new" as far as the *language of science* is concerned, because of its being directly related to the way of reasoning and proceeding of the sciences. Ideally, the options utilising traditional methods and the options utilising new technologies should complement each other, avoiding repetitions and making the corresponding different types of creativity converge into an articulate and complete approach.

The importance of interactive options in the education to the correct usage of language in the sciences remains valid for the new technologies. These technologies actually enable an expansion of possibilities, as they are apt both for classroom interactions (where their use is easily incorporated into teacher-students and students-students interactions) and for individual study (computer-student interactions at the computer-student interface). The former may comprise attractive possibilities like multiple entries from different sources (individual students and also the teacher) for the same discourse. The latter becomes a sort of dialogue that needs to offer complete guidance to an individual student, stimulating his/her attention and providing enough answers for clarifications to be satisfactory and effective.

The challenges inherent in the design of new-technologies options for the aspects considered in the previous section increase as the complexity of the given aspect increases. The design of options to stress the importance of the correct selection of individual words (which is the technically simplest among the aspects considered in the previous section) can span through a variety of possibilities whose use is sufficiently simple and straightforward. Simple interactive exercises may ask to select a correct word for a given statement out of a set of proposed words, and provide explanations for each word (why it is correct or why it is not), accessible to the student after he/she makes a selection. When possible, visualizing the actual meaning of incorrect choices can greatly contribute to generate durable impressions, so as to prevent the repetition of the same error (the generation of durable impressions being one of the routes through which error analysis is effective); moreover, it can simultaneously contribute to the development of visual literacy (the ability to associate mental images to descriptions and vice versa), which is severely hampered by inadequate language-mastering [44]. For instance, for the incorrect statement considered in the previous section, "*The equations for real gases consist of the parameters .....*", a blank space will be left in place of the verb; the verbs proposed for selection will include *contains*, *consists*, and others that might have been encountered in students' writings on real gases equations; the explanation associated with *contains* will explain that it informs that the parameters are present in the equations, but are not the only items present; the explanation associated with *consists* will explain that its use implies that only those parameters are present in the equations, and nothing else; the visualization associated with *contains* will show the complete equations (e.g., the van der Waals equation), possibly highlighting the parameters; the visualization associated with *consists* will show only the parameters, and some sentence or symbol would aptly warn that this is meaningless.

The design of effective student-computer interactive options for the analysis of clauses and sentences requires deeper investigation, because of the rapid increase in the number of factors to be taken into account, as the number of words in a clause, or the number of clauses in a sentence, increases. Affordable approximations may be based on the analysis of errors and ambiguities in students' writings and select specific issues within otherwise correct statements, or pose a set of questions with reference to an incorrect statement, to foster reading and proofreading abilities. For instance, the questions on an incorrect statement like "*Particles in an atom vibrate around the nodes of crystal lattice*" can include: "What kinds of particles are there in an atom?", "What are the nodes of a crystal lattice?", "What occupies the nodes of a crystal lattice?", "In which cases the nodes of a crystal lattice are occupied by atoms?", "Which entities vibrate around the nodes of a crystal lattice?", and, finally, the question that more directly counteracts the error in the incorrect statement "Can the particles constituting the atom vibrate independently around the nodes of a crystal lattice?"; correct answers need to be accessible after the student has made pre-scheduled selections. The major drawback of options of this type is that they need to be personalized, so that they can address errors that are frequent in a specific context of among specific groups of students. Therefore, the option would likely be better realized in the form of a software enabling teachers to enter incorrect statements, the corresponding questions and the correct answers. This, however, brings another question, as such an option would require good language abilities, good pedagogical abilities and good content knowledge from individual teachers – a combination that is not very frequent. Possible answers may be sought through networking, with experts available to assist individual teachers to develop the options that are more suitable for their specific context.

The design of interactive options focusing on the identification of logical relationship can make use of flow charts and highlight relationships between the boxes of the flow chart and the pieces of information in a statement or a discourse. Ideally, guided constructions of flow-charts could be designed for the student-computer interface. It could also be possible to design options apt for two or more students working together for their individual study.

VIII. DISCUSSION AND CONCLUSIONS

Experience shows that inadequate language mastering corresponds to poorer performance in science disciplines, both because of greater difficulties at understanding the material (that is communicated through language and requires language for reflecting on it) and because of difficulties at expressing acquired knowledge. Not only individual concepts remain unclear, but, when language mastering inadequacies become extensive, they unavoidably determine poor conceptual understanding, inadequate perceptions of fundamental distinctions like the distinction between systems (physical objects) and processes, or physical reality (comprising systems and processes) and the tools that we utilise to describe them (equations, diagrams, etc), and general lack of familiarization with the scientific approach (which requires internalization of the awareness of these distinctions up to the point that the correct selection of the corresponding terms becomes spontaneous). Students' performance is severely affected.

The development of abilities that are fundamental for science learning, like logical and reasoning abilities, visualization ability, or the ability to recognise and utilise the description roles of mathematics, closely depend on the degree of language-mastering. It is therefore particularly important to familiarize students with the mode of expression typical of the sciences, in order to enable them to understand all the information conveyed by a text (or other material), to adequately communicate information when they are required or wish to, and to learn to utilize the other communication instruments that are important in science and technology communication, from diagrams and other images to equations.

The familiarization with the *language of science* needs to rely on specific attention to language aspects within the teaching and learning of science and technology disciplines. The design of options to this purpose is particularly challenging, because of the variety of the needed language skills, from the ability to select correct individual words to the identification and expression of individual logical or method-related relationships (e.g., cause-effect, hypothesis-thesis, condition-consequence) and of comprehensive logical and interpretation frameworks. The ultimate objective is to enable the student to be comfortable with the complexity of scientific discourses and, therefore, to be comfortable at reading or writing the complex sentences that are needed to express those discourses.

The design of options will ideally include both traditional approaches utilizing books and classroom interactions and approaches based on new technologies, utilizing student-computer interfaces. Approaches utilizing classroom interactions are particularly apt to attract students' attention on issues (like language aspects) that would otherwise often be overlooked, and to enable responses (by the teacher) that are both real-time and specifically tailored to the individual students' need. Computer-based options can be created both for classroom use and for the students' individual study. Although lacking the contribution multiplicity of some classroom activities (like, e.g., the collaborative in-class constructions of flow-charts to identify and represent logical frameworks), the student-computer interactive options can foster moments of individual reflection that can be complementary to the classroom activities and bring the advantages of individual study. The combination of both options (individual study and classroom group activities) cumulates their advantages while minimizing drawbacks.

The current work has focused mostly on the importance of language-mastering, without giving large space to the issue of the language of instruction, because this issue has been extensively discussed in other works [18, 21–24, 46]. It is however considered important to stress the relevance of the mother tongue as the ideal ground to learn the correct usage of language and the specific usage that is typical of science communication (because of the greater familiarity with it), to learn reasoning and logic (because we think using it), to learn the logic of language and to learn to recognize the intimate integration between language and science; the last two aspects are more easily and completely acquired within the mother tongue and, once acquired, can be transferred to any other language that the student wishes to utilize, because they are skills that overcome the border of individual languages. The design of approaches based on new technologies can include approaches to stress the cross-language character of these aspects and, consequently, the cross-language character of the requirements of the *language of science*.

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