The Fibonacci Project

DISSEMINATING INQUIRY-BASED SCIENCE AND MATHEMATICS EDUCATION IN EUROPE

Background Resources For Implementing Inquiry in Science and Mathematics at School

Learning through Inquiry

WITH THE SUPPORT OF

EUROPEAN COMMISSION

SEVENTH FRAMEWORK PROGRAMME

Resources for Implementing Inquiry in Science and Mathematics at School

The Fibonacci Project (2010-2013) aimed at a large dissemination of inquiry-based science education and inquiry-based mathematics education throughout the European Union. The project partners created and trialled a common approach to inquiry-based teaching and learning in science and mathematics and a dissemination process involving 12 Reference Centres and 24 Twin Centres throughout Europe which took account of local contexts.

This booklet is part of the *Resources for Implementing Inquiry in Science and in Mathematics at School*. These Resources include two sets of complementary booklets developed during the Fibonacci Project:

1) Background Resources

The *Background Resources* were written by the members of the Fibonacci Scientific Committee. They define the general principles of inquiry-based science education and inquiry-based mathematics education and of their implementation. They include the following booklets:

- 1.1 Learning through Inquiry
- 1.2 Inquiry in Science Education
- 1.3 Inquiry in Mathematics Education

2) Companion Resources

The *Companion Resources* provide practical information, instructional ideas and activities, and assessment tools for the effective implementation of an inquiry-based approach in science and mathematics at school. They are based on the three-year experiences of five groups of Fibonacci partners who focused on different aspects of implementation. The *Companion Resources* summarise the lessons learned in the process and, where relevant, provide a number of recommendations for the different actors concerned with science and mathematics education (teachers, teacher educators, school directives, deciders, policy makers...). They include the following booklets:

- 2.1 Tools for Enhancing Inquiry in Science Education
- 2.2 Implementing Inquiry in Mathematics Education
- 2.3 Setting up, Developing and Expanding a Centre for Science and/or Mathematics Education
- 2.4 Integrating Science Inquiry across the Curriculum
- 2.5 Implementing Inquiry beyond the School

Reference may be made within this booklet to the other *Resource* booklets. All the booklets are available, free of charge, on the Fibonacci website, within the *Resources* section.

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Learning through Inquiry

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Introduction

Educating a new generation in natural sciences and mathematics is a long process. It is now agreed that the process is most efficient when it begins early, as early as preschool, and continues through subsequent years of schooling for as long as possible. It is also widely recognised that this education should be aimed at *all* children and youngsters, no matter what their future professional or education paths might be. Although consensus on these two points has emerged – in Europe as well as in other parts of the developed, emerging or developing world – a fundamental issue remains: what is the pedagogy to be implemented to achieve this ambitious goal of a quality science and mathematics education for all? As a corollary, what qualities are needed by teachers to practise this pedagogy? And how can one best help these teachers? The Fibonacci project was probably one of the first large-scale attempts in Europe to explore these questions concretely in science and mathematics, whilst respecting the necessary distinctions between inquiry pedagogy in these two domains. On the basis of the three-year experience of the Fibonacci project, this booklet aims to clarify these issues for all who are concerned with science and mathematics education.

Excellent examination results in education can be achieved by teachers dedicated to their students and their subject, no matter what pedagogy is practised. However, a large number of research and development projects, carried out over several decades around the world, indicate that when done well, an *inquiry* pedagogy can provide the means for students to understand concepts rather than simply memorise them. This approach contrasts with those where facts and processes are learned with little understanding, a situation leading to boredom at school, an inability to apply the knowledge in daily life and poor long-term acquisition of knowledge.

Section 1 of this booklet considers the nature of inquiry in the disciplines of science and mathematics as a precursor to considering, in Section 2, the common aspects of inquiry pedagogy applied to mathematics as well as to science. It should be noted that at the primary school level, science and technology are frequently interwoven either explicitly in the curriculum or implicitly in practise. The Fibonacci project chose not to try to distinguish between them but to assume that what is described as the inquiry pedagogy in science also applies to technology in situations where they are combined. Sections 3 and 4 outline the specificities of an inquiry pedagogy when dealing with science and mathematics respectively, leading to conclusions regarding the fundamental differences between inquiry pedagogy in these two areas of education. Section 5 considers the use of Information and Communication Technologies (ICT) in inquiry learning and cross-disciplinary approaches in relation to an inquiry-based pedagogy in science. An inquiry-based pedagogy requires some structure for organising classroom work and to underpin the learning process. The key features of an inquiry pedagogy are summarised at the end of the booklet.

Nonetheless, this booklet is no more than an introduction to inquiry pedagogy applied to science and mathematics, and would be insufficient to guide those interested in implementing a rejuvenated science and mathematics education in the classroom and in inspiring teachers' practises. Two other Fibonacci Background Booklets provide such necessary and important details: *Inquiry in Science Education* and *Inquiry in Mathematics Education*. Further, five Fibonacci Companion Booklets provide practical information, instructional ideas and activities, and assessment tools for effectively implementing an inquiry pedagogy in science and in mathematics[1]:

- *Tools for Enhancing Inquiry in Science Education*
- *Implementing Inquiry in Mathematics Education*
- *Setting up, Developing and Expanding a Centre for Science and/or Mathematics Education*
- *Integrating Science Inquiry across the Curriculum*
- *Implementing Inquiry beyond the School*

[1] All Fibonacci Background and Resource Booklets are available at www.fibonacci-project.eu, in the *Resources* section.

1. Inquiry in science and mathematics

Science and mathematics provide powerful insights into the world and the wider universe. They enable us to construct knowledge and, together, allow us to appreciate the wonders of the natural world. In both, a dominant mode of knowledge building is through inquiry, and in this section we discuss how this is conceptualised in mathematics and in science. We recognise, however, that in a document this brief we may over-simplify complex positions and ideas.

Mathematics deals with abstract constructions (such as numbers, geometrical shapes, algebraic structures) and the relations between them. Yet the abstract character of this subject does not prevent it emerging also from observations of the natural world (for instance regarding spatial forms and their regularities), from questions raised in other fields such as physics, biology, computer science or economics, and from technical challenges (for instance, how to build planar representations of 3D objects). The result is an extremely powerful form of knowledge, which not only constantly develops itself but presents a tremendous wealth of applications in almost all areas of human activities, with all branches of mathematics and not just traditional applied mathematics being involved today. Mathematics is a deductive science whose results are established through logical deduction, but this does not prevent it from having an experimental dimension which is more and more developed thanks to technological advances. Such characteristics explain why mathematics cannot be disconnected from science and technology, neither in education nor in the scientific world.

Science deals with the natural world, its objects and phenomena. Scientists, through a number of processes including inquiry, build and test models of how the world works. These models exist in various forms, including analogies, mathematical models and detailed descriptions. The models allow scientists and the wider public to discuss and debate sometimes complex phenomena with a view to improving our understanding. The knowledge that science builds may emerge from evidence collected in the process of making and testing predictions through experiments or observations; this evidence always has the potential to alter, improve and even sometimes profoundly change the existing models. In the quantitative description of the world, science needs mathematics or other abstract symbols when it reaches the limit of what can be expressed using everyday language. In addition, and probably more importantly, the symbols and operations of mathematics enable computations of all kinds to be made on an immense quantity of abstract objects. Within science, different disciplinary fields distinguish themselves either by the tools they use (astronomy differs from biology) or by their mode of access to reality (geology differs from chemistry). What they share is a desire to build knowledge that is increasingly valid and reliable in ways that are systematic and, when applicable, reproducible.

These brief considerations show that these two realms of knowledge are clearly distinct. In mathematics, *problems* are considered, and *proof* as to whether a claim is true or false results from a logical demonstration. In science, *facts* and *questions* are considered, and *models* emerge from the process of observing, experimenting, interpreting and so on. However, the same considerations show they also have much in common. This commonality can inspire some fundamental aspects of a common pedagogy. In the most generally accepted meaning of the term, inquiry is an *act of building and testing knowledge*. This process requires the *active role* of the student, the learning of science starting with *questions* rather than answers, and drawing on what is already known, but going beyond it.

2. Inquiry pedagogy in the Fibonacci project

2.1 *Why inquiry?*

The reason for emphasising inquiry-based education in the Fibonacci project is that, carried out effectively, it facilitates understanding. Learning with understanding is different from remembering facts such as the names of the planets in the solar system, which particular objects float or sink or multiplication tables in mathematics. This is not to say that facts are not important, but rather that they are insufficient for developing understanding alone. Information needs to be organised to be useful with isolated pieces brought together to form principles and concepts which can be used in making sense of new events and phenomena. The important thing is for students to understand why things do or don't float, not just what does or doesn't float. But principles and concepts cannot be directly transmitted to learners, except as meaningless words to be learned by rote; they must be (re)created and appropriated by the learner's own thinking. For this reason we need to consider how understanding – be it in science, mathematics or any subject – may develop.

2.2 *Learning through inquiry*

Research evidence shows that when students encounter something new to them, they attempt to make sense of it using ideas formed from earlier experiences. These ideas become modified as students use them to try to explain new experiences. In this process an idea can be used to make a prediction and then tested by seeing if the evidence from the new experience agrees with what was predicted. If it does, then the idea becomes just a little 'bigger' because it explains a wider range of phenomena. Even if it doesn't 'work' – and an alternative idea has to be tried – the experience has helped to refine the idea. Through these processes there is a quantitative change in terms of the range of events and phenomena that can be understood, but there is also a qualitative change in the nature and scope of the ideas. Scientific ideas that are widely applicable are necessarily context-independent, as, for example, the idea of what makes things float that can be used for all objects and all fluids. To move from an idea of why a particular object floats in water to the big idea of floating is a large step which involves making connections between observations in very different situations. Similarly, ideas of how to solve particular types of mathematical problems, by, for example, involving fractions or negative numbers, are built up through bringing together experiences of tackling a range of related problems. In some cases, a conceptual step may also force us to deconstruct, then to reconstruct a new and more encompassing idea. Ideas developed in this way are only understood if they make sense to the learner as products of their own thinking. This view of learning argues for students to have experiences which enable them to make sense of different aspects of the world. First-hand experiences are important, particularly for younger children, but all learners need to develop the skills used in testing ideas – questioning, predicting, observing, interpreting, communicating and reflecting.

2.3 *Inquiry and cognitive development*

The cognitive development of mind and understanding is a complex process, onto which experimental psychology and neuroscience are shedding some light. We are still far from making education an exact science. Nonetheless, a comparison with medicine before and after Louis Pasteur is probably relevant. Scientific understanding of the biochemical functioning of the human organism has undoubtedly enhanced the quality of medicine, but it would be inappropriate to reduce the role of a physician to a merely technical one. Similarly, understanding the processes of cognition, communicating to teachers what is known about attention, memory, learning, and neuronal evolution with age, may help them to better adjust their practise, without neglecting the value of the human relationship established by any good teacher with their students.

The inquiry principles and their implementation are supported by cognitive research and discoveries. Providing young children with a rich environment promotes their neuronal development, especially up to the age of the puberty. Organising and facilitating dialogue in the classroom stimulates sociability and contributes toward the development of understanding. Giving students a chance to express themselves in their own words and to write their own opinions, hypotheses and conclusions through a free and collaborative process increases their self-confidence. Discovering that boys and girls show the same curiosity and ask the same questions when facing natural phenomena and trying to understand them, is a way to reduce gender segregation in future professional paths.

2.4 *Developing inquiry-based pedagogy*

Inquiry-based education requires teaching skills and classroom relationships that vary considerably from those associated with traditional teaching. What is noted in the IAP report of the Working Group on Science Education (2009) is relevant to all learning: "The aims of modern education and of inquiry-based education in particular require students to become more independent learners. This means teachers developing new relationships with students and having the confidence to allow students to develop their own ideas."[2]

Most teachers will require a considerable time to adopt the roles, beliefs and practises that are required in inquiry-based teaching. Moreover the views of learning held by school management and parents may need to change to support a different conception of learning. As well as time, such changes depend on teachers' understanding of the nature of inquiry, which is best achieved through experiencing it for themselves as part of professional development.

2.5 *Evaluation and assessment of student learning*

There is an understandable desire to want answers to questions about the impact of inquiry-based education on students' achievement. Before any attempts are made to assess impact on students' learning, however, it is first important to ensure that they are indeed experiencing inquiry-based education. Considerable changes in teaching are generally needed and until these have become embedded any evaluation based on student outcomes is likely to generate misleading data about the impact of inquiry. Instead, evaluation is best directed at the classroom processes and used to improve implementation of learning through inquiry. Similarly, the assessment of students' ideas and skills is best used as feedback for teaching to help learning. Indeed, this formative use of assessment is an essential part of inquiry-based teaching. Information about students' learning is gathered by teachers observing, questioning and studying the products of students' work as part of their regular interactions, rather than from formal tests which often tend to assess memorised facts.

[2] Harlen, W. and Allende, J. (2009). Report of the working group on teacher professional development in pre-secondary inquiry-based science education (IBSE). Interacademy Panel on International Issues.

3. Inquiry pedagogy in science education[3]

Scientists use a wide range of methods and approaches to build new knowledge, but underpinning them all is a desire for reliable and valid data about phenomena in the natural world that can be tested and reproduced by peers. Inquiry-based science education encourages students to develop their scientific skills, independently or in collaboration, in such a way that they can appreciate the processes that many scientists use in their everyday lives. Students come to appreciate that scientific knowledge can be tentative and that doing science doesn't simply involve a set of linear steps towards an end goal. Science inquiry can be fuelled by inquisitiveness as well as necessity and can bring out the best of a person's creativity and inspiration while rewarding patient endeavour.

The teacher's role in inquiry-based science education includes the selection and matching of the student's task with the nature of the scientific knowledge to be learned. The teacher's choice of topic and activity will depend on a range of factors including the local or national curriculum that they are following, the resources available to them, and the interests and abilities of their students. Many teachers have not experienced this approach to science education themselves to any great depth and will need opportunities to develop their pedagogy through professional development.

The process of inquiry can begin by trying to make sense of a phenomenon, or answer a question, about why something behaves in a certain way or takes the form it does. Initial exploration reveals features that recall previous ideas leading to possible explanations. There might be several ideas from previous experience that could be relevant and through discussion one of these is chosen as providing a possible explanation or a hypothesis to be tested. The test of the hypothesis is whether there is evidence to support a prediction based on it, for only if ideas have predictive power are they valid. To test the prediction, new data about the phenomenon or problem are gathered, then analysed and the outcome used as evidence to compare with the predicted result. This is the 'prediction à plan and conduct investigation à interpret data' sequence in Figure 1. More than one prediction/test is desirable and so this sequence may need to be repeated several times.

From these results a tentative conclusion can be drawn about the initial idea. If it gives a good explanation then the existing idea is not only confirmed, but becomes more powerful because it then explains a wider range of phenomena. Even if it doesn't 'work' and an alternative idea has to be tried (one of the alternative ideas in Figure 1), the experience has helped to refine the idea; so knowing that the existing idea does not fit is also useful. This is the process of building understanding through collecting evidence to test possible explanations and the ideas behind them in a scientific manner, which we describe as learning through scientific inquiry.

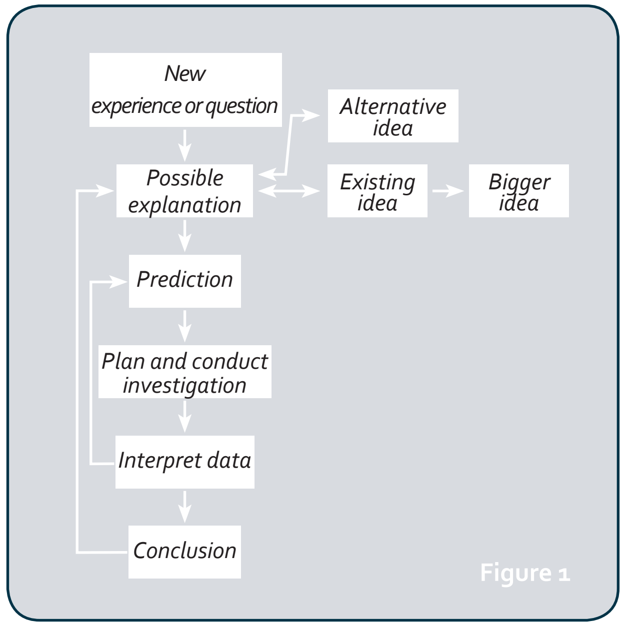

Figure 1

[3] This section is greatly expanded in the Fibonacci Background Booklet *Inquiry in Science Education* and in the Companion Booklet *Tools for Enhancing Inquiry in Science Education*, both available at www.fibonacci-project-eu, in the *Resources* section.

4. Inquiry pedagogy in mathematics education[4]

In the Fibonacci project we consider that inquiry-based education is appropriate not only for the learning and teaching of science but also for the learning and teaching of mathematics. Here we point out the similarities and some differences between the characteristics of inquiry-based education in mathematics and science.

As is the case in the natural sciences, inquiry-based mathematics education refers to an education which does not present mathematics to pupils and students as a ready-built structure to appropriate. Rather it offers them the opportunity to experience:

- how mathematical knowledge is developed through personal and collective attempts at answering questions emerging in a diversity of fields, from observation of nature as well as the mathematics field itself, and,
- how mathematical concepts and structures can emerge from the organisation of the resulting constructions, and then be exploited for answering new and challenging problems.

Inquiry-based practises in mathematics involve diverse forms of activity: articulating or elaborating questions in order to make them accessible to mathematical work; modelling and mathematising; exploring and experimenting; conjecturing; testing, explaining, reasoning, arguing and proving; defining and structuring; connecting, representing and communicating. Inquiry-based mathematics education engages students in these forms of activity and fosters the development of associated skills.

It is expected that the inquiry-based approach will improve students' mathematical understanding, which will result in their mathematical knowledge becoming more robust and functional in a diversity of contexts beyond that of the usual school tasks. It will help students develop mathematical and scientific curiosity and creativity as well as their potential for critical reflection, reasoning and analysis, and their autonomy as learners. It will also help them develop a more accurate vision of mathematics as a human enterprise, consider mathematics as a fundamental component of our cultural heritage, and appreciate the crucial role it plays in the development of our societies.

If it is to be more than a slogan, inquiry-based mathematics education requires the development of appropriate educational strategies. These strategies must acknowledge the experimental dimension of mathematics and the new opportunities that digital technologies offer in support. The history of mathematics shows that such an experimental dimension is not new, but over the last decades technological developments have put a large number of new resources at the disposal of mathematics which have made the experimental dimension more visible and shared by the mathematical community. Compared with experimental practises in natural science, however, one must keep in mind that the terrain of experience for mathematics learning is not limited to what is usually called the "real world".

As they become familiar, mathematical objects also become the terrain for mathematics experimentation. Numbers, for instance, have been used for centuries and are still an incredible context for mathematics experiments, and the same can be said of geometrical forms. Patterns play a great role in mathematics, whether they are suggested by the natural world or fully imagined by the mathematician's mind. Playing with patterns is a stimulating mathematical activity in the context of inquiry, even for elementary school children. Digital technologies also offer new and powerful tools for supporting investigation and experimentation in these mathematical domains. Inquiry-based mathematics education must, therefore, not just rely on situations and questions arising from real world phenomena, even if the consideration of these is of course very important, but use the diversity of contexts which can nurture investigative practises in mathematics.

[4] This section is greatly expanded in the Fibonacci Background Booklet *Inquiry in Mathematics Education* and in the Companion Booklet *Implementing Inquiry in Mathematics Education*, both available at www.fibonacci-project.eu, in the *Resources* section.

Mathematics has a cumulative dimension to a greater extent than science. Mathematical tools developed for solving particular problems need to build on each other to become methods and techniques which can be productively used for solving classes of problems, eventually leading to new mathematical ideas and even theories, and new fields of application. Moreover, connections between domains play a fundamental role in the development of mathematics. Thus it is important in implementing inquiry-based mathematics education that students not deal only with isolated problems, however challenging they may be, since this process may not enable them to develop the over-arching (or more generally applicable) mathematical concepts.

Selecting appropriate questions and tasks for promoting inquiry-based mathematics education thus requires the consideration of their potential according to a diversity of criteria, and the building of a coherent organisation and progression among these, having in mind the characteristics of mathematics as a scientific discipline and the ambition of such education of emphasising the interaction between mathematics and other scientific disciplines, between mathematics and the real world.

A further crucial point is that, even when they emerge from real world situations, mathematical ideas are not directly accessible to our physical senses, and are thus worked out through a rich diversity of semiotic systems: standard systems of representation such as graphs, tables, figures, symbolic systems, computer representations, etc., but also gestures and discourse in ordinary language. Inquiry-based mathematics education must be sensitive to this semiotic dimension of mathematical learning and to the progressive development of associated competencies, without forgetting the evolution in semiotic potential and needs resulting from technological advances.

Modern technological tools have an impact on inquiry-based education through the immediate access given to a huge diversity of information, whatever the topic. This situation means that the "milieux" in which students can interact in investigative practises are potentially much richer than those usually used for developing investigative practises in mathematics. However, the necessity of selection and the critical use of such information create new demands that inquiry-based mathematics education must take into account.

5. Aspects of implementing inquiry learning

5.1 *Using Information and Communication Technologies*

Information and Communication Technologies (ICT) provide powerful tools for supporting inquiry-based education in mathematics and science. These tools are quite diverse and include:

- specific educational interfaces developed for supporting the collection and analysis of experimental data in a diversity of scientific domains;
- microworlds attached to specific scientific or mathematical domains, as in mathematics the various software tools for algebra, calculus and geometry;
- simulation tools such as Net-Logo which make it possible to explore the behaviour of complex systems and identify regularities often not easily accessible through pure analytic work;
- more general tools such as spreadsheets, statistics software, tools for numeric and symbolic computations and for graphical representations, not necessarily designed for education but convertible into educational tools.

Most of these ICT tools, implemented on hand-held devices or computers, have been present in the educational arena for several decades. Their potential for supporting experimental practises and inquiry-based learning in science and mathematics has been investigated by educational researchers and attested in experimental settings. However, their influence at large on mathematics and science education has remained quite limited. The situation is improving, however, as EU projects (e.g. Intergeo and InnoMathEd) and national projects (e.g. in the Netherlands and Germany) show.

In the last decade, Internet technology has substantially modified this educational landscape in several ways:

- making many of these technologies accessible online, and leading to new forms of educational objects, such as "applets" (small interactive software components that can be accessed through an Internet browser);
- providing easy access to a huge amount of information, whatever the question at hand, and to professional databases;
- leading to an exponential increase in the number of resources produced both for students and teachers, by individuals, collectives or institutions, and changing the usual patterns of production and dissemination;
- supporting the development of collaborative practises by both students and teachers, and the development of networks.

Dynamic worksheets which are increasingly used for supporting inquiry-based learning in mathematics and science illustrate this move. Following the idea of a traditional worksheet, a dynamic worksheet is a document written in HTML that includes applets to be viewed at the computer screen. This technical basis enables the integration of texts, graphics and dynamic configurations. The learning environment can productively combine experiments on the computer screen with more traditional paper and pen work where the students are required to take notes and make sketches in their study journals. The potential offered by ICT for supporting inquiry-based practises in mathematics and science education, for moving from local to global influences and successes, is thus substantially transformed.

This being said, we would like to stress some important points. ICT offers evident potential for supporting inquiry-based learning in mathematics and science. This does not mean that ICT tools must be given a predominant role. Experimental work can and must also develop using more traditional objects and technologies. Virtual experiments should not replace real experiments. These are especially important for approaching new fields and domains of experience. For instance, adequate development of spatial and geometrical knowledge by young students cannot be achieved only by using Dynamic Geometry Software (DGS), whatever the quality of its use. It also requires working with objects and models in different spaces, not just in the micro-space of the sheet of paper or the computer screen.

ICT offers evident potential but actualising this potential requires appropriate tasks and guidance from the teacher. As shown by research in this area, real creativity must be developed in terms of tasks, and not just by adapting to the ICT environment tasks which have proved to be effective in more standard environments. This makes collective elaboration and exchange of resources especially important. The same can be said regarding teachers' practises. Benefiting from the learning potential of ICT technology requires that teachers provide new forms of orchestration and guidance whose requirements have been underestimated until recently.

In summary, ICT has created a new ecology for an inquiry pedagogy in mathematics and science education, but the requirements in terms of design and teacher experiences must not be underestimated.

5.2 *Cross-disciplinary approaches*[5]

Primary schools usually employ generalist teachers who teach all subjects, although in some countries some specialisation may exist. This situation has great advantages for science education, since mathematics and natural science lessons can be embedded in a whole cognitive development of the child. The essential and necessary connection between science and language acquisition can develop quite naturally with the use of a science or experiment notebook, evolving from free expression by the child to the choice of progressively more accurate vocabulary, organisation of thought into adequately constructed sentences, proper use of tenses

[5] This section is greatly expanded in the Fibonacci Companion Resource Booklet *Implementing Science Inquiry across the Curriculum*, available at www.fibonacci-project.eu, in the *Resources* section.

(e.g. implying causality), etc. Other logical methods of information coding may also develop, such as graphs, schemas and diagrams, drawings, etc. Expressing scientific observations, reasoning and conclusions with clear formulations in everyday language is a prerequisite, too often bypassed in the secondary school by an excessive use of formulae learned by heart. This connection of science to the acquisition of written and oral mastery of the mother tongue has proven extremely fruitful in many inquiry-based science education pilot projects.

Beyond a direct connection of science to language, history also offers numerous pedagogically fruitful opportunities to establish links with science. From its very beginning, the development of science has been an extraordinary human adventure, which easily arouses the interest of children and youngsters. Narratives describing people, attempts and errors, failures and success, controversies and proofs can be fascinating, especially when placed against the cultural and technological background of the times. Conversely, it might be fruitful to compare causality in the case of a scientific observation – e.g. the sun rising in the morning, or a volcano erupting – and in the case of an historical event – e.g., the causes of World War I.

Art is another subject which is often proposed to be connected with science and mathematics, a connection which may take many forms: from aesthetics (e.g. in geometry) to the discovery of natural shapes and symmetries, from the choice of materials or pigments to the rules of construction in architectural design.

The list of linked subjects could continue with geography, sport, health education: in each case, inquiry learning sequences can be constructed while closely blending these subjects with mathematics or science.

In middle and secondary schools, the presence of specialised teachers renders such links more difficult to implement in practise, although they could be even more fertile than in primary school thanks to the deeper knowledge teachers have of their own discipline. Obstacles here are not of a different nature from the ones mentioned above between scientific disciplines, but the knowledge background of a language, sport or art teacher may create more distance from science, and vice-versa, than cultural differences inside scientific disciplines. To exploit the rich potential of interdisciplinarity in secondary school, more efforts appear necessary.

6. Inquiry pedagogy and transition from primary to secondary school

The boundary between primary and secondary education is somewhat variable among countries. Most have preschool, then primary school beginning at age 5 or 6 and lasting five or six years. Secondary school may be separated into two levels, junior high school (post-primary school) up to the age of 13 or 14, followed by high school. In some countries, all children attend the same kind of secondary school, while in others there is a selection process at the end of primary school, with pupils then attending either more vocational or more academic schools. Education of some kind is compulsory to the age of 16 in most countries.

6.1 *Relevant differences regarding science and mathematics education*

Despite this relative diversity of systems, in relation to science and mathematics education generally the same three factors apply when children move from primary to post-primary school.

First, the primary teacher often has no particular specialisation and is able to teach all subjects, including science and mathematics. The training of these teachers is usually focused on pedagogy, child development, language acquisition and health more than on a specific academic discipline. By contrast, teachers in post-primary schools have most often been trained in a particular discipline (e.g. life science) or a combination of two closely related ones (e.g. physics and maths, or physics and chemistry), and have a higher academic degree (bachelor and often masters). Thus there is often a significant difference in science and mathematics knowledge, understanding and approach between the two populations of teachers, and their approach to inquiry might have to be dealt with in different manners. However, teacher vocational training schemes are not identical among countries, and are also subject to change.

Second, pupils in primary school are children, while in secondary school they rapidly become teenagers, entering into an age of considerable changes (puberty, affective responses and social relations, etc.). In addition to cognitive and affective changes, the horizon of secondary school is also marked, for a significant fraction of pupils and their parents, by the career decisions to be made around age 16.

Third, the pressure of curriculum becomes more intense in secondary school. Although many countries have recently introduced high stakes pupil assessment in primary school, with mixed results, the pressure becomes greater in post-primary.

Assessment is usually focused on knowledge, recalling facts and answering exercises that rarely mobilise problem solving skills. Learning through inquiry aims at: creativity, critical thinking, language abilities, experimental skills. Teachers are under pressure to complete the curriculum and are often led to "teach to the test". If testing is judged important, then the tests should be built to measure valuable attainments and not facts learned by heart.

6.2 *Consequences for inquiry education in secondary schools*

Most of the pilot projects promoting an inquiry-based pedagogy in the last two decades (1990-2010) have been in primary schools. The class teacher configuration has been advantageous to the introduction of learning through inquiry. While the teachers' lack of scientific knowledge is a disadvantage, which training and coaching may partly address, this lack may also make the teacher more sensitive to the discovery path of the student. By contrast, secondary school science and mathematics teachers seem to be less amenable to inquiry-based teaching: trained in science or mathematics, their focus is more on the content of the subjects rather than the process of learning. In addition, adolescents often do not see the point of much of what they are intended to learn; they need to find their work interesting and relevant to their lives. Finally, the time required to pursue inquiry effectively is not easily accommodated in existing school schedules and is not compatible with the assessment pressure.

Since research and studies show that inquiry pedagogy can also be recommended for secondary education, its implementation needs precise answers and strategies to overcome these serious obstacles. For example:

- There are advantages in engaging teachers who have a good science background. However, in many countries the traditional pedagogy that teachers are used to often leads them to prefer to conduct an experiment as a demonstration for the whole class, rather than have groups performing and discussing it in parallel. Laboratory work would often be prescribed by a detailed protocol, allowing minimal engagement of the student. Teachers need help in the form of professional development and concrete examples to change from a whole class to a more group-based pedagogy.
- The specialisation in separate subjects (e.g. physics, Earth science, etc.) often comes too early in secondary education. In accord with the 'science for all' objective, which today underpins science education, the most important aspect for students is to understand the broad fundamental ideas of science and science as a process, rather than accumulating a more or less heterogeneous collection of facts and knowledge. The unity of science, possibly including technology, is difficult for students to grasp, when their own teachers are prisoners of disciplines separated by walls, each of them with specific methods and specialised languages. Students with social difficulties or from a poor cultural environment are the first to suffer from these useless (at this stage) academic subtleties. What would help here is to define some big ideas in science, to be addressed in a completely interdisciplinary manner. This strategy does not mean that teachers are to be trained as generalists, equipped only with a vague science content. Indeed, their excellence in a scientific field, properly validated by their training, can be a guarantee of their ability to explore and learn related fields, in order to teach interdisciplinary science at the secondary level. In some experimental programmes (France), one observes that teachers progressively accept that they can say "I don't know" faced with a student's hypothesis or question, and complete this answer by "but I will search and tell you more next time!"
- The more children have their curiosity fed and their autonomy aroused in primary school, the more they will accept inquiry-based learning in secondary school, and the more teachers will be able to use this lively curiosity and autonomy to organise inquiry-based sessions and groups with success. It is noticeable that in such classes, both boys and girls often react positively to the challenges of an inquiry-based lesson.

Despite the science qualification of secondary school teachers, and precisely because of these real obstacles to the implementation of inquiry education, it is essential to organise properly this transition between primary and secondary schools. Expert primary school teachers and trainers can contribute to a dialogue with specialised secondary school teachers. Classroom activities, prepared for the end of primary school, can usefully be adapted for early secondary school. Teacher professional development and new inquiry-based teaching resources, available locally or on-line, are absolutely necessary to change the pedagogy. As a long-term goal, a continuous progression from early primary to the end of compulsory education, focusing on the big ideas in science and acquisition of competencies, could be the aim of an integrated inquiry-based science curriculum.

In mathematics, similar contrasts are experienced between the primary and secondary teachers' culture, and the fact that many school teachers have not only a limited mathematical background but also a problematic affective relationship with the discipline adds to the challenge. The fact that the teaching of mathematics (at least arithmetic and some geometry) has always been compulsory in educational systems from the early grades and is considered to be a discipline per se contributes to its isolation. Due to the importance given to mathematics in this way, and the difficulty it presents to many students, the teaching of mathematics has been the focus of considerable research attention. As a result, teaching strategies, frameworks and resources have been developed that inquiry-based mathematics can build upon.

Conclusion: Key features of inquiry pedagogy

We summarise here the nine key features of the inquiry pedagogy adopted in the framework of the Fibonacci project[6]. They apply both for mathematics and science education and are recognisable throughout the preceding sections of this booklet.

- **Developing a problem-based culture**. Developing a *problem-based* culture aims at a large variety of tasks and problems that allow individual approaches and various ways to solve a problem. Learning science through inquiry is described in terms of a *question-based* culture. In mathematics, it is also fruitful to explore questions that are not in the form of problems to be solved.
- **Working in a scientific manner**. Mathematics and science share some specific ways of thinking and operating. Education goes much beyond simple instruction, as it aims at conveying these specific approaches as a special but powerful *process* of knowledge. Standard teaching methods too often narrow the role of experiment in either field, mathematics or science, relying only on deductive and formal presentations. Inquiry attempts to make the student act, within obvious limitations, similarly as to how a scientist does today, or has done in the past (hence the importance of connecting the lessons with their historical background).

[6] What we call here "key features of inquiry pedagogy" is consistent with the general use of the concept of inquiry throughout this booklet. These "key features" originated from aspects of inquiry developed in the eleven "modules" upon which the German SINUS project (1998-2007) was based.

- **Learning from mistakes**. Mistakes should be regarded as constitutive of learning, and be considered as opportunities for learning and not only as learning barriers. Students may come into science classes with many conceptions which may be regarded as false from a scientific perspective. However, these conceptions may provide fruitful interpretation patterns in some everyday situation. Proper learning strategies will use these as building blocks toward progress to more scientific views.
- **Securing basic knowledge**. Learning does not mean collecting single, isolated elements of knowledge. For learning to be successful, students must become able to establish and consolidate their own *thinking net*. The more connections they establish between elements of knowledge, i.e. the denser and tighter the thinking nets are woven, the more flexible and rich learning becomes. It is only then that basic knowledge can serve as solid basis for understanding, creative processes and support problem-solving or questioning activities.
- **Cumulative learning**. Improving one's knowledge means integrating new items into previously acquired knowledge. Moving in this way from *additive* to *cumulative* learning represents a deep change. What is learned has to be linked to knowledge already acquired and to issues to be learned in the future (the so-called principle of *vertical linking*). Connecting the current learning task to the global sequence, from beginning to end, illuminates the student's understanding. It should be noted that this is often disregarded or overlooked in traditional mathematics or science education.
- **Experience subject boundaries and interdisciplinary approaches**. Mathematics and science education can establish intimate relations with language or history. Broader extension of this interdisciplinarity can be considered, for example with arts, where the aesthetic dimension of mathematics and science can be exploited, as well as the role of scientific knowledge in the development of the arts in various civilisations.
- **Promoting the participation of girls and boys**. When observing girls and boys in a classroom conducting inquiry, when looking at their science notebooks, when listening to the discussions and arguments in groups doing an experiment, it is often difficult to see a gender differentiation in interest, abilities or passion. On the other hand, studies – such as *Relevance of Science Education* (ROSE) – indicate a persistence, at the age of 15, of different patterns of interest – for instance technical objects for boys and health issues for girls. Emotions and feelings, which play a capital but often ignored role in school interests and achievements, are common to boys and girls but follow different development patterns. Both genders may also react differently to issues which appear in public debate, such as climate change or the acceptable use of some technologies. This diversity, when it manifests, is a rich source of complementarities which the teacher can exploit while placing the lesson in different and appealing contexts.
- **Promoting student cooperation**. Cooperative learning has been given particular attention in research and pilot projects to improve learning in general. Cooperation does not only support the development of social abilities, but also leads to deeper cognitive gains. The role played by language during discussion develops verbalisation, argumentation and dealing with discrepant opinions.
- **Autonomous learning**. This point is especially critical in terms of students who are classified as low achievers. Whether they come from low-income families, ethnic minorities, broken social backgrounds or elsewhere, they have in common feelings of isolation, or even abandonment, in the school context and are faced with the cultural ambitions that school cultivates. Lacking the family or community support other students enjoy, they slowly drift to a lack of interest for all school activities and challenges. Inquiry pilot projects have revealed, in various social and cultural contexts, that such a low-achievement slope is not inevitable. Progressively restoring students' self-confidence, providing the language they need to express themselves rather than rote learning, exhibiting the often hidden resources of any individual represent a progressive conquest of autonomy that inquiry pedagogy has demonstrated.

Further reading

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A number of research projects and pilot projects across the world over several decades have indicated that an *inquiry* pedagogy, at its best, can provide the means for students to understand rather than simply memorise concepts. What, then, are the characteristics of an inquiry pedagogy in the natural sciences and mathematics that can lead to the ambitious goal of quality science and mathematics education for all? What skills do teachers need to practise this pedagogy? And how can one best help teachers to acquire them? The Fibonacci project was one of the first large-scale attempts to explore these questions in a concrete manner both in science and mathematics, whilst respecting the necessary distinctions between inquiry pedagogy in these two domains.

Beginning with a reflection on the nature of inquiry in science and mathematics and on the similarities and differences of inquiry pedagogy applied to science and to mathematics, this booklet aims to clarify these issues for all who are concerned with science and mathematics education.

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