Problem-solving in technology education: the role of strategies, schemes & heuristics

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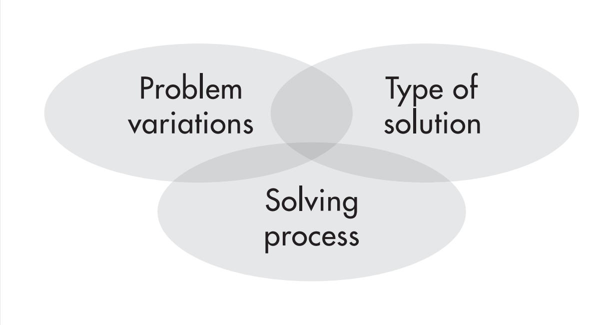
Introduction

Problem-solving is considered one of the most complex intellectual functions. In spite of the fact that the nature of human problem-solving has been studied by psychologists over the past 100 years, the term has remained rather ambiguous. Some of the questions often discussed regarding problem-solving are: Is there a general method for solving problems in different areas and contexts? What characterizes a good problem-solver? To what extent can people learn problem-solving methods and improve their competencies in this regard? This chapter addresses these questions, with particular emphasis on teaching and learning technology in K-12 education. An effort will be made to propose a rationale for teaching pupils inventive problem-solving methods beyond the 'classical' problem-solving model often discussed in technology education literature. The chapter will end with a reflection on teaching this type of course to Israeli teachers and pupils, and conclusions about the effectiveness of teaching problem-solving methods.

Is there an all-purpose problem-solving method?

The question characterizing problem-solving in technology cannot be separated from the broader question - is there a general problem-solving method? This question is very difficult and ancient as well; Aristotle's works contain much regarding both. Let us examine concisely what two renowned educational philosophers wrote on this issue. John Dewey (1859-1952) had made problem-solving the very model of thinking (although he did not put it that way). In his 1910 book, "How We Think", Dewey distinguished five steps in thinking (or, as he put it, reflection), and what he described are in the steps involved in problem-solving: *'Upon examination, each instance reveals, more or less clearly, five logically distinct steps: (i) a felt difficulty; (ii) its location and definition; (iii) suggestion of possible solution; (iv) development by reasoning of the bearings of the suggestion; (v) further observation and experiment leading to its acceptance or rejection; that is, the conclusion of belief or disbelief '* (Dewey, 1910).

In mathematics, ideas about problem-solving hark back to the mathematician George Polya, who pointed out in his book, "How to solve it", the following four stages in solving a problem: (a) understanding the problem; (b) devising a plan; (c) carrying out the plan; and (d) looking back. One can see that Polya's stages in solving problems very much resemble Dewey's suggestion. However, Dewey saw problem-solving as a kind of thinking (as opposed to, say, 'idle thinking'). Although Dewey called his book "How We Think" and not "Physical Thinking" or "Mathematical Thinking", he emphasized that thinking is always directed towards some



01 The three dimensions of problem-solving.

difficulty requiring unraveling, and therefore always takes place in a specific context. Indeed, during the last couple of decades, many voices have supported the ‘domain specific’ perspectives on learning, thinking and teaching. These include authors like Robert McCormick at the Open University in England (2004), David Perkins at Harvard University and Gavriel Salomon at Haifa University (Perkins and Salomon, 1989). In these circles, problem-solving must occur within a context and depends strongly on an individual’s previous experience in similar situations. Perkins and Salomon, in their contribution entitled *‘transfer of learning’* in the “International Encyclopedia of Education” (1992 edition), stress that transfer of learning from one context to another hardly occurs, and transfer to closely related contexts and performances (*‘near transfer’*) seems to have a much better prospect than transfer to rather different contexts (*‘far transfer’*). However, according to these authors, education can be designed to promote conditions fostering transfer, as will be discussed later in this chapter.

We can conclude this discussion by saying that no all-purpose problem-solving method exists, but there are some problem-solving approaches or representations that can be useful over several disciplines, and other methods that are unique to each subject separately. Technology educators, as well as educators in other fields, need to acknowledge diverse problem-solving approaches and be able to utilize them in different class contexts.

Accordingly, this chapter aims at highlighting several approaches for solving technological problems that have gained increased attention in areas such as engineering and management, and that could also be useful in technology education in K-12 schooling.

Is there room in the school curriculum for teaching special lessons in school for fostering general thinking skills, such as problem-solving or creativity?

What do technology, science or mathematics teachers know about problem-solving in subjects beyond their fields of expertise?

The nature of technological problems and their solutions

The term ‘problem’ expresses a state of difficulty, a situation, condition or issue that needs to be resolved, or a question raised for consideration for solution. What types of problems do we present to students in technology education? What kinds of solutions do we expect them to arrive at? Since this question relates closely to the more general question of what is technology, I will follow the approach suggested by Marc de Vries in his book “Teaching about technology: An introduction to the philosophy of technology for non-philosophers” (2005), in which he describes technology as *‘the human activity that transforms the natural environment to make it fit better with human needs, thereby using various kinds of information and knowledge, various kinds of natural (material, energy) and cultural resources (money, social relationships, etc.).’* We can combine this perception with the broader problem-solving model seen in image 01 (David H. Jonassen, 1997) to depict problem-solving in a technological context.

02 How would you compare these three batteries?

The three ovals are shown as partially overlapping each other to indicate that no sharp borders exist between the problem definition, the solving process and the solution itself, and that problem-solving is not a linear process. This model can help, however, in exploring problem-solving in technology, as discussed below.

‘Problem Variations’ is concerned, in general, with the context a problem is derived from, the setting, environment or background the problem relates to, its degree of complexity (specific versus multifaceted), degree of structuredness (well-structured versus ill-structured) and domain specificity (situated versus abstract). What makes a problem difficult to solve? The term ‘ill-defined problem’, which is often used in the psychological and educational literature, indicates that the difficulty level of a problem is first determined by problem definition or presentation, or in other words, problem variations. Consequently, this is the first dimension of the problem-solving model seen in image 01. According to John Hayes (1978), ill-defined problems require solvers to contribute to the problem definition, such as reducing a general query to a specific question or a set of questions, making assumptions and determining criteria for a satisfactory answer. For example, if one is asked to compare the quality of three car batteries and no additional details are given, the solver has to determine what parameters to take into account. These might include the maximum current (in amperes) a battery can supply; its capacity (in ampere hours); the Cold Cranking Amps (CCA) parameter, which is the number of amperes a battery can support for 30 seconds at a temperature of 0°C; product maintenance requirements; price; and manufacturer’s warranty.

Unlike problems in mathematics and science, solving technological problems often involves social norms and values. In the current example, these can be the implication of each battery's production or recycling in saving the environment, or the work conditions each manufacturing company provides to its employees.

How can we engage pupils in formulating problems as part of conventional teaching?

03 The Mango phone and an Israeli newspaper cutting announcing its release.

What do you think about asking pupils to suggest original questions for a class exam?

It is important to note that technological problems do not always arise from considering the explicit needs of individuals or society (food, clothing, housing, transportation, etc.), as is often presented in the educational literature. Many technological systems, for instance the microwave oven or the cellular telephone, were originated by inventors and engineers pursuing a technical possibility rather than in response to a request by people, simply because individuals cannot ask for products they have never heard about.

The cellular telephone has responded to more than known needs. The advent of this artefact and its related services such as texting, also known as SMS (Short Message Service), have created a new technological market in response to previously unidentified needs.

To conclude, technological problems are often derived from several contexts and can involve social, economical, mathematical, scientific or technical aspects. Writers such as Marc de Vries (2005) and Charles Harris and his colleagues, in their book "**Engineering Ethics, Concepts and Cases**" (2000), argue convincingly that technological problem-solving and engineering in particular have to deal with issues such as moral dilemmas, ethical questions, responsibility, integrity, reliability, risks, safety and environmental issues.

The *'Type of Solution'* regards the way a solution to a problem is put into practice, for example by changing the physical ttributes or function of components in a system or the entire system. Sometimes, but not always (as people often think), a technological problem is solved by the development of a new artefact or system. It is important to emphasize, however, that the essence of a solution to a technological problem is the idea behind the solution, while its practical application can appear in many forms.

For example, an increasing number of today's technological systems are computerized, and technological problems are frequently handled through programming. Consider the following story: when the first generation of cellular telephones appeared on the market in the mid-1990s, the calls were so expensive that most organizations or families could not afford using this service. This was undoubtedly a technological problem having strong technical, economical and social aspects: how to limit people in using the telephone under only urgent or pressing circumstances. An Israeli company came out with a unique cellular telephone model called **Mango**, which was a regular cellular telephone in which the entire keyboard except for one key was blocked electronically; the user could receive calls but dial to only one pre-programmed number. The Mango was accepted as an innovative product, as seen in image 03.

The Mango was very successful on the market at the time: companies bought it for their out-of-house employees to keep in contact with the office, and parents gave it to their children to call home. In this case, a small functional change in an existing artifact, which solved the problem of limiting the cost of its use, enabled exposing people from diverse backgrounds to a new technology, which in turn advanced the entire field of cellular communication.

The Mango case demonstrates that the term problem-solving in technology expresses a broader concept than the term design. Although many people consider these terms equivalent, it is worth mentioning that, unlike the concept of design, technological problem-solving does not always end up with the development of a new product.

Do you agree that a design always ends up with a new product?
Can you think of an example that disproves this 'rule'?

'The Solving Process', the third dimension in the problem-solving model (see image 01), involves the method, course or procedure of proceeding from a given state to a desired goal state; this is the focus of the rest of this article.

Many people see problem-solving as a two stage process: first comes the collection of a wealth of ideas or optional solutions to a problem, and only later comes the examination of these ideas more systematically and the selection of the optimal one. Accordingly, terms such as 'thinking outside the box', 'free flow of thoughts', 'associative thinking' or 'brainstorming' are often mentioned in the context of problem-solving in technology. These terms, however, are used less in mathematics and science. This two stage view of problem-solving has become somewhat of a barrier for teaching problem-solving methods in school for two reasons: first, the concept of 'disordered thinking' is often perceived as strange, odd, inconsequential and not serious in comparison to convergent thinking, which characterizes problem-solving in science and mathematics; second, there is an inherent contradiction in trying to teach people to think in an unexpected way or to arrive at surprising ideas.

To learn more about the role of divergent thinking in solving technological problems, it may be instructive to ask the question: To what extent do expert problem-solvers use 'disordered thinking' as a working method? Phillip C. Wankat and Frank S. Oreovicz, who broadly discuss the issue of problem-solving in their book "**Teaching Engineering**" (1993), compare the ways novices and experts solve problems as follows: *'While novices memorize knowledge as small disconnected facts, experts have thousands of "chunks" of specialized knowledge and patterns stored in their brains in a readily accessible fashion; while novices have difficulties in describing* *a problem, experts use many techniques to re-describe or re-define a problem; while novices use trial-and-error, experts use strategies; while novices do not break a problem into parts or harder problems, experts analyze parts, proceed in steps and look for patterns.'*

There is a wide consensus in the literature that experts tend to concentrate on a problem and use specific strategies to seek a solution to a problem rather than rely on a random search, as novice problem-solvers frequently do (Joanne G. Kurfiss, 1988). David Jonassen (1997) specifically stresses that individuals who use domain-specific strong strategies are better problem-solvers. Experts use strong strategies effectively and less experienced solvers can also learn to use them (Mayer, 1992). Margaret Boden (2004), a researcher having a background in computational psychology and artificial intelligence, also stresses that constraints, as opposed to random search or free flow of thought, make creativity possible. According to this author: *'To throw away all constraints would be to destroy the capacity for creative thinking. Random processes alone, if they happen to produce anything interesting at all, can result only in first-time curiosities, not radical surprises… randomness can sometimes contribute to creativity, but only in a context of background constraints.'*

John Hayes (1978) distinguishes between random search to a solution, which he calls *'the most primitive search process'*, and heuristic search, in which the problem-solver uses knowledge to identify promising paths in seeking a solution.

We can see, then, that in contrast to what many people believe, organized thinking and the consideration of prior knowledge and constraints can contribute to successful problem-solving more than methods like 'irregular thinking' or 'associative thinking'. Lately, there is a growing recognition that inventive problem-solving often requires the integration of divergent and convergent thinking, and good problem-solvers frequently use these two types of thinking simultaneously or alternate easily between them (Frank Barron, 1969; Dennis R. Brophy, 1998; Paul A. Howard-Jones, 2002).
Arthur Cropley (2001) claims that the mere production of variability via divergent thinking runs the risk of generating only 'quasi-creativity' or 'pseudo-creativity' if it is not explored and evaluated via convergent thinking. Jacob Goldenberg and David Mazursky (2002), in their book "**Creativity in Product Innovation**", point out that most brainstorming groups do not generate more or better ideas than individuals working independently. To get an inventive (simple, surprising but efficient) idea, one does not necessarily need to collect many ideas; it can be more useful to utilize strategies or thinking patterns that help in seeking a solution through altering systematically with the physical and functional attributes of a system's ingredients. Some of these methods are discussed on the following pages.

Strategies, schemes and heuristics for solving technological problems

Alex Osborn (1963) and Bob Eberle (1977) suggested the SCAMPER method for inventive problem-solving, which is mainly a framework of 'playing' with the traits and functions of components in a system, or their interrelations.

- **Substitute:**
  What could be used instead?
  What other components could be used?
- **Combine:**
  What parts or functions could be combined?
  What unrelated ideas or parts could we combine with this?
- **Adapt:**
  What else is like this?
  What could be copied?
  What idea could be incorporated?
- **Magnify:**
  What could be magnified, enlarged or extended?
  What could be exaggerated?
  What could be added?
  How about greater frequency?
  What could add extra value?
  What could be duplicated?
  How could it be carried to a dramatic extreme?
- **Modify:**
  Could we change an idea, practice or product slightly and be successful?
  What new twist could we introduce?
  What changes could be made in the plans?
- **Put to other uses:**
  What else could a specific component be used for?
  Are there new ways of using it?
  What else could be made from this?
- **Eliminate or divide:**
  What could be omitted or eliminated?
  What is not necessary?
  What could be condensed?
  Divided up?
  Split up?
  Separated into different parts?
- **Rearrange:**
  What other arrangement might be better?
  Other patterns?
  Other layouts?
  Other sequences?
  Change the order?
  Transpose cause and effect?
  Interchange components?
- **Reverse:**
  What are the opposites?
  What are the negatives?
  Reverse roles?
  Consider it backwards?
  Should I turn it around?
  Do the unexpected?

The case of the Mango cellular telephone mentioned earlier demonstrates the principle of solving a problem by eliminating a central component from the configuration of a system along with its function. In this case, the keyboard keys were not physically removed, rather their function was blocked.

04 Pharos of Alexandria.

Jacob Goldenberg and David Mazursky (2002) show how 'the displacement template' in their terms is helpful in solving technological problems and developing surprising products; by removing legs from a chair, for example, we receive a chair useful on the ground, such as on beach sand.

Perhaps one of the most comprehensive works on inventive problem-solving in engineering was carried out by the Russian researcher Genrich Altshuller (1988) and his colleagues, who investigated the principles and knowledge that characterized more than a million patents and inventive solutions to technical problems. Altshuller's method, entitled TRIZ (the Russian acronym for the Theory of Inventive Problem Solving), comprises the following three stages:

(a) the resolution of technical and physical contradictions in a system;
(b) the evolution of systems;
(c) the reference to the ideal system and ideal solution.

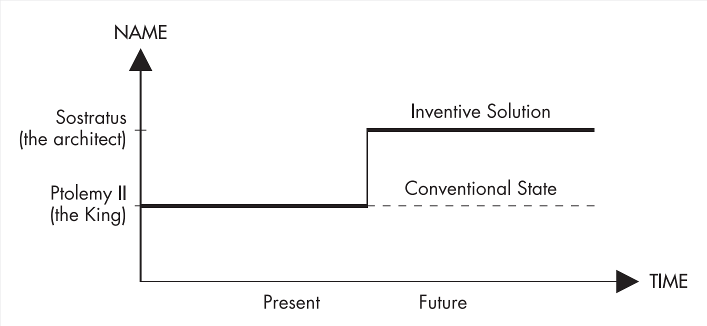
Since TRIZ is not easy to learn or describe, it is often presented in the literature through “40 Techniques for Overcoming System Conflicts” such as (the first 10):

- Segmentation
- Extraction
- Local Quality
- Asymmetry
- Combining
- Universality
- Nesting
- Counterweight
- Prior counter-action
- Prior action

TRIZ is gaining increased attention in the world of engineering, design and creative problem-solving, and has been implemented in large corporations such as Motorola, Xerox, Kodak, McDonnell Douglas, General Motors, Ford and General Electric. At Rolls Royce, hundreds of engineers have been trained in TRIZ, which has become an integral part of the company's problem-solving culture.

Based on the roots of SCAMPER and TRIZ, Israeli researchers (Horowitz, 2001; Horowitz and Maimon, 1997; Goldenberg et al., 1999) developed a simplified version entitled 'Systematic Inventive Thinking' (SIT) or 'Advanced Systematic Thinking' (ASIT) that has been implemented successfully in a large number of companies in Israel and worldwide (Barak and Goffer, 2002). This method offers seeking a solution to a problem by the following manipulations with the system's ingredients:

- **Unification:** assign a new function to an existing component.
- **Multiplication:** introduce a copy (or slightly modified copy) of an existing object into the system.
- **Division:** decompose an object into its parts; slice, cut, snip or divide an object.
- **Eliminate:** remove an object from the system along with its function.



05 Solving a problem by making a connection between two variables.

- **Change relationships** between variables in a system; add, remove or alter the dependency between physical or functional attributes of components in a system.

Roni Horowitz (2001) suggested the 'closed world' principle, according to which an inventive solution to a problem is based on using existing resources in the 'world of the problem' or its closed environment. A conventional solution to a problem, on the other hand, often requires using extra resources such as components, materials or energy. The following example demonstrates how the 'change relationships between variables' template mentioned above can help in finding an inventive solution to a problem.

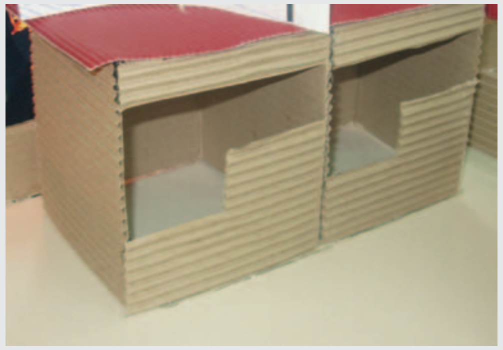
The Lighthouse of Alexandria, seen in image 04, was built in 3rd century BC and is considered to be one of the Seven Wonders of the World. Sostratus, the Lighthouse's architect, wanted his name to be perpetuated in the Lighthouse design. This was not allowed by Ptolemy II, the King of Egypt, who ordered his name to be carved on the huge structure. How could the architect solve this problem?

The lighthouse question was presented to 9th grade pupils who were studying a course in inventive problem-solving and to other pupils who served as a control group. The pupils who did not study the course suggested only a few solutions, such as writing the architect's name on the rear of the building, inside the building, or on a sign outside the building. The pupils who studied the course, in contrast, suggested many ideas, including:

- To carve architect's name in such a way that it could be seen from a distance;
- To hide architect's name graphically in a decoration on the building;
- To integrate architect's name graphically in the King's name;
- To write architect's name in a language unknown to the King (e.g., Chinese);
- To cast architect's name in a light beam to be seen at a distance by the lighthouse projectors.

Several pupils suggested ideas that were very close to the way Sostratus solved the problem: as history tells us, he first carved his name on the lighthouse, put plaster over it and then carved the King's name. After a number of years, the plaster bearing the King's name disintegrated and Sostratus' name appeared to one and all.

We can see that some pupils used the principle of solving a problem by assigning a new function of components that already exists in the system, for example the King's name or the light beam. Sostratus' solution, as some of the pupils also suggested, is based on the principle of adding a connection between a variable in the system, as illustrated in image 05.



06 A universal dual-level counter for an amusement park: the aim is to enable wheelchair-bound individuals to buy tickets or play games next to other people.

The diagram in image 05 illustrates that while in a conventional state the King's name is permanently displayed on the building, the inventive solution is based on a change in the value of the variable Name (King's, architect's) over Time (present, future). Certainly, time is often an important factor (variable) in technological systems. Goldenberg and Mazursky (2002) demonstrate how the principle of adding connections between variables is useful in inventing interesting marketing ideas.
For example, imagine yourself calling a takeaway pizza service in which the price of the pizza depends on the delivery time: the longer you wait, the less you pay! What about connecting the pizza's price to its temperature? The idea of 'All You Can Eat' in many restaurants is based on the opposite action: eliminating the relationship between what or how much people eat and the price they pay.

?

Try drawing a graph that illustrates the concept of improving a system by 'changing relationships between two variables' for the two pizza takeaway services or the 'All you can eat' method promotion mentioned above;
Use another independent variable (horizontal axis) for your graph.

Outcomes from running inventive problem-solving courses to teachers and junior high school pupils

In this section I will describe the experience gained during several courses for inventive problem-solving with Israeli science and technology teachers and 9th grade pupils. The courses, which lasted about 15 meetings of two hours each, combined learning methods such as brainstorming, parts of de Bono's (1986; 1990) CoRT program, and inventive problem-solving principles derived from SCAMPER, TRIZ and ASIT described above. I have documented and evaluated some of the courses by videotaping class activities, interviewing the participants, analyzing the assignments the pupils or teachers prepared, and administrating pre-course and post-course quizzes and attitude questionnaires in the class (see Barak, 2006; Barak and Mesika, 2007). The following points of interest emerged from the courses.

- Many participants, teachers and students alike, commented that during the course they started to observe that many instruments or technological systems at home or on the street are based on the 'inventive principles' they learned. For example, a TV remote-control is just a modified version of an on-apparatus keyboard (the duplication principle), decaffeinated coffee utilizes the concept of eliminating a central ingredient from an existing product, and designating a road lane only for buses and taxis is based on connecting two or three variables in the system (type of vehicle, road lane location and time of day).

- Some pupils reported that they started using the 'inventive principles' they learned at home or in other subjects they studied at school. For example, a girl reported that when her mother asked her to clean the carpet in her room, she asked her: *'Why do I even need this carpet? Let's "delete" it.'* Later, when the mother asked her to clean the carpet in the living room, she said *'But it's such a difficult job.'* The mother responded, *'Then go and "duplicate" yourself.'* This example shows that the girl brought home the 'terminology' she had learned in the course and even taught her mother to implement this thinking pattern.

- A pupil reported that when she saw her mother arranging her clothes in her closet - winter clothing on the lower shelves and summer clothing on the higher ones, she suggested another method: to place the more useful clothes lower down, and the other clothes higher up. In the girl's world, she applied here the principle of 'making a connection between variables' that she had learned in the course.

- Many participants of inventive problem-solving courses mentioned that although at first they used the principles they had learned discreetly, gradually the diverse methods blended in their minds and they were often unable to state exactly what method had helped them in finding a specific solution. For example, in an 'amusement park' project, a group of pupils sought a method to allow pupils with disabilities to enjoy the park just like everybody else. They designed a universal model of a dual-level counter, seen in image 06. This counter could be used for ticket-selling, food-selling or shooting galleries often found in amusement parks. The pupils were convinced that they had applied the method they had learned in the course, but had difficulty in specifying whether they had used the 'duplication' principle, the 'division' principle or the 'change symmetry' approach. Actually, as the pupils said, the different methods they had learned frequently overlapped. For the pupils it is important that they can use appropriate methods fluently to find good ideas.

Although the follow-up of the above-mentioned experimental courses offered to teachers and pupils showed encouraging results, much further work is required to explore how people grasp the concept of 'systematic' problem-solving, and how 'ordered' and 'disordered' thinking merge in the problem-solving process.

Concluding remarks

This article puts forward the argument that inventive solutions to problems are often found through focused thinking, consideration of constraints and continued efforts, rather than by spontaneous discovery. We have seen that surprising but utilitarian solutions to problems are frequently based on using resources that are already available in 'the world of the problem' and its closed environment. People can learn how to systematically seek original solutions to problems by methods like assigning new functions to existing components in a system or changing relationships between variables in the system. However, one should consider these methods as flexible strategies and heuristics rather than as strict algorithms, and regard 'ordered' and 'disordered' thinking as complementary methods in problem-solving.

> The discovery of penicillin by Sir Alexander Fleming in 1928 is often presented as an example of serendipity - the phenomenon of valuable discoveries by accident. On the other hand, there are those who claim that 'unexpected discoveries' always occur in the background of hard work and a wide knowledge base. What does your experience show in this regard?
> Will the teaching of problem-solving methods to pupils foster or impede their aptitude for finding original solutions to problems?

To conclude this chapter, let us return to the question of whether there is any benefit in teaching problem-solving methods, and to what extent people can transfer learning and thinking skills from one context to another. David Perkins and Gavriel Salomon (1992) point out that although the preponderance of studies suggests that transfer comes hard, a closer examination of the conditions under which transfer does and does not occur, and the mechanisms of transfer, present a more positive picture. These authors highlight several conditions and instructional approaches under which transfer might appear, such as:

- Thorough and diverse practice of performance in questions in a variety of contexts that can yield a flexible, relatively 'automatized' bundle of skills easily evoked in new situations;
- Including in the learning the explicit abstraction of principles and critical attributes of a given situation;
- Fostering active self-monitoring and reflection on one's thinking processes by teaching children not just to apply a specific strategy but also to monitor their own thinking processes in simple ways; and
- Arousing mindfulness and alertness to the activities one is engaged in and to one's surroundings, in contrast with a passive reactive mode in which cognition and problems unfold automatically and mindlessly (see, for example, Ellen Langer's 1997 book entitled "The Power of Mindful Learning").

Utilizing instructional approaches of the type identified above in class can encourage pupils to apply the problem-solving strategies they have learned in new contexts in school and outside it.

> What kind of investigation could you carry out in your classroom to explore the role of 'ordered' and 'disordered' thinking in solving technological problems?

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