Chapter 4

TEACHING THINKING SKILLS AND SCIENCE KNOWLEDGE: TWO COMPETING OR TWO COMPLEMENTARY GOALS?

1. LEARNING AND TEACHING

The thinking project is great. You know what the problem is? It's the curriculum. If we are going to spend so much time on developing students' thinking, how will they ever learn all that they are supposed to know?
(From a teacher who participated in a TSC teacher workshop)

Teachers who participated in the TSC professional development courses often expressed the concern quoted above. Although the idea of engaging in higher order thinking appealed to many teachers, they were worried that "wasting" valuable time on teaching thinking might undermine their ability to achieve what they see as their main role as science teachers – to teach science contents. Such a concern does not fit current views about the nature of knowledge and how it is acquired. Perkins (1992) summarizes these views by saying that at a minimum, we want our schools to achieve three goals with regard to the knowledge they teach: retention of knowledge, understanding of knowledge and active use of knowledge. A summary phrase for the goals taken together might be "generative knowledge"—knowledge that does not just sit there, but functions significantly in people's lives to help them understand and deal with the world.

How may these three goals be achieved? Perkins replies by saying that what we need is thoughtful learning. This may be achieved if schools focus not merely on fostering memories but on schooling minds in educational settings rich with thinking-centered learning, where students learn by thinking about what they are learning:

The rationale can be boiled down to a single sentence: Learning is a consequence of thinking. Retention, understanding, and the active use of knowledge can be brought about only by learning experiences in which learners think about and think with what they are learning... The conventional pattern says that first students acquire knowledge.
only then do they think with and about the knowledge that they have absorbed. But it’s just the opposite: Far from thinking coming after knowledge, knowledge comes on the coattails of thinking. As we think about the content we are learning, we truly learn it. (Perkins, 1992, p. 8, italics in original)

Indeed, continues Perkins, this even holds for the simplest kind of learning, straight memorization. Perkins reviews studies demonstrating that people memorize best when they analyze what they are learning, find patterns in it, and relate it to knowledge they already have. Perkins quotes William James who expressed this idea as early as 1888:

...The art of remembering is the art of thinking.... When we wish to fix a new thing in either our own mind or a pupil’s our conscious effort should not be so much to impress and retain it as to connect it with something else already there. The connecting is the thinking; and if we attend clearly to the connection, the connected thing will certainly be likely to remain within recall (Perkins, 1992; italics are James’s).

Therefore, teaching thinking and teaching content are not two distinct educational goals that compete for our most valuable educational resource – time. Rather, these two goals support each other: On the one hand, deep thinking requires rich content to think about. The traditional school subjects with their rich conceptual networks may provide many appropriate contexts for thinking. On the other hand, learning school subjects in a meaningful way that would lead to acquisition of generative knowledge requires that content to be learned thoughtfully. This idea was formulated in the following way:

To teach by using concepts generatively is, happily, to teach content and skills of thinking at the same time. This is the real meaning of the Thinking Curriculum, where concepts are continuously at work in contexts of reasoning and problem solving...The Thinking Curriculum joins content and skill so intimately that both are everywhere (Resnick & Klopfer, 1989, p. 6)

These theoretical considerations are the cornerstones of the TSC project that is founded on the belief that teaching higher order thinking according to the infusion approach (i.e., teaching thinking skills as explicit educational goals within detailed science topics) should support rather than interfere with the acquisition of science knowledge. This general assertion, however, needs to be closely examined: What would the combination of thinking and content look like in specific learning activities or in actual classroom situations? Is there empirical evidence that learning according to this approach indeed results in an increase in students’ knowledge? These issues are addressed in what follows.

2. THE INTERPLAY OF CONTENT AND THINKING IN CLASSROOM EPISODES

In the TSC project explicit thinking goals are combined with specific content goals. What does this theme look like in actual learning? In what follows we shall look at two classroom episodes from the perspective of examining the relationships between thinking and content goals.

2.1. THE ROLE OF FERTILIZER IN SEED GERMINATION

The main thinking objective of the Seed Germination microworld is to teach variable control (see Chapter 3 for detailed description). The content objective of the activity is to teach various issues that pertain to seed germination. Let us see how reasoning may support knowledge construction.

As described in Chapter 3 one of the five variables in this microworld is fertilizer. The activity asks students to conclude whether adding fertilizer affects germination rate. Students’ initial belief regarding this issue is that the addition of fertilizer increases germination rate. The source of this belief is probably students’ informal knowledge that is based on their out of school experiences with gardens or potted plants in their homes. According to these experiences “fertilizer is good for plants”. However, once they begin to control variables and draw valid inferences, the evidence students obtain from the experiments they conduct with the Seed Germination microworld points to a different conclusion, namely that adding fertilizer does not affect germination rate. This conclusion conflicts with students’ initial knowledge about fertilizers. Invariably, in all the classes in which students engaged with this activity, the following type of conversation took place:

S: I don’t understand. Something is wrong here. Look what I did (student showing her activity sheet, in which she performed two experiments, the first with and the second without fertilizer. The level of the other four variables remained the same in the two experiments).
T: Why do you think something is wrong?
S: Because I did it right. I changed only fertilizer and kept all the other four factors unchanged, but the outcome is the same: I got 60% germination in both experiments. So it’s wrong because it comes out that fertilizer doesn’t matter.
T: And what’s wrong with that?
S: Because I know that fertilizer is good for plants.
T: Is that always so? Do you remember what we said when we discussed the structure and function of seeds?
S: Yes. Seeds contain an embryo and nutrients.... Oh... Right! Seedlings first get the materials they need from the nutrients that are preserved in the seed. So that’s why fertilizer does not affect germination rate—because plants only need it later on after they germinate....

Such a conversation took place in many classrooms between students and teachers. It often also took place in many of the TSC teachers’ workshops, between teachers and workshop leaders, indicating that many science teachers share the same misconception as their students, namely, that seedlings need to get nutrients from the environment in order to germinate. These cases illustrate that when reasoning processes triggered by the TSC learning activity take place within science content, the conclusion of a sound, rational reasoning process may contradict with students’ initial knowledge, creating a cognitive dissonance. It is important to note that in these circumstances the dissonance does not follow from an experience with the physical world or from social discourse (i.e., other individuals who may contradict one’s own beliefs), but from an individual’s own reasoning processes.

In this particular example the teacher led her student to review the facts she had learned in class in an earlier lesson (about the structure of seeds). This guidance helped the learner in making the connection between that knowledge and the conclusion from her computer assisted investigation thereby developing her understanding that fertilizer is indeed only required after germination. Although this
learning process was not formally assessed, it is reasonable to assume that it contributes to students’ understanding of the structure and function of seeds.

2.2. Human reproduction and hormonal control

The second example is taken from a 12th grade biology lesson. The knowledge goals of that lesson consisted of the female reproduction system and hormonal controls. The thinking goals were the analysis of a piece of knowledge and its application to solving a new problem. After the teacher explained the development of pregnancy she asked the following question:

If my goal is to terminate the pregnancy by using a pill, where could I block the process (i.e., the pregnancy process)?

A detailed description of the discussion that followed is beyond our scope because it requires elaborate knowledge about hormones. However, the teacher’s comments in an interview that took place after the lesson show how she views the integration of knowledge and thinking in that part of her lesson:

[When I asked where the process could be blocked...]. Their discussion was at the level of the controls of the reproduction system. I am referring to their thinking, to a student who can look at the information he learned in class from a high vantage point. To analyze it. They did it very well... Then I took them one step forward by asking “Let’s suppose the block is not at this level - where else, in what additional points can the process be blocked?” And they discovered it - the inhibitor of Progesterone. What does it discharge? This is a piece of information that they did not have. I know it is similar to Progesterone, they did not know it - a steroid that is analogous to Progesterone. [The teacher provided this piece of information when it was needed]. And I really liked it when a student asked why it (i.e., the analogue) would bond before the progesterone. I really liked it because this is about enzyme competition - something we never learned and never mentioned in class”.

Students processed the information they had learned in class by analyzing the relationships between the scientific concepts, by creating new connections between pieces of information, and by requesting new information, thereby applying their knowledge to solving a new problem. Taken together these classroom episodes demonstrate how engagement with reasoning processes in the context of specific science content may contribute to students’ scientific knowledge. However, these episodes do not provide a formal assessment of whether or not the TSC learning activities indeed support students’ science knowledge.

3. COMPARING STUDENT’S KNOWLEDGE IN TSC AND NON-TSC CLASSROOMS

In order to investigate empirically whether evidence indeed shows that the TSC learning materials support the learning of science content, students’ knowledge was assessed at the end of two TSC units: The Genetic Revolution unit and Water Balance in Living Organisms unit. The Genetic Revolution unit addressed argumentation skills in the context of selected topics in Human Genetics in 9th grade. The Water Balance in Living Organisms unit addressed scientific and critical thinking skills. The topic of that 8th grade unit is the role of water in life processes. Both units were assessed by using a research design that included an experimental group that studied the TSC learning materials and a comparison group that studied the same topics by conventional methods. A knowledge test was administered to students in the experimental and comparison groups at the end of the program as the term exam in biology. The experimental and comparison groups learned these topics for the same amount of time (Zohar, Weinberger & Tamir, 1994; Zohar & Nemet, 2002; see Chapter 5 for more details). It is important to note that the two groups had very similar results in reasoning pre-tests taken at the beginning of the study, confirming an initial equivalent level of students from both groups.

In order to assess the effect of the Genetic Revolution unit on students’ genetics knowledge, we analyzed a knowledge test that included 20 multiple-choice items. Most of the items were taken from previous years’ matriculation exams (assessing a non-accelerated, basic level biology course). Topics that are not normally covered by the matriculation exam were covered by items that were written especially for this test by the TSC project team. An expert checked content validity of these items.

The results of the knowledge test show that students in the experimental group scored significantly higher than students in the comparison group (\(\bar{X} = 72.9, S.D = 6.0\) and \(\bar{X} = 59.4, S.D = 4.1\) respectively, \(t = 3.94, P < 0.001\), see Table 1).

In order to assess the effect of the Water Balance in Living Organisms unit on students’ biological knowledge, we analyzed another knowledge test that included 20 multiple-choice items. The items were taken from a test designed by the authors of the textbook “Water Balance in Living Organisms” that was used for studying that unit (Rosenbloom, 1984).

The results of the knowledge test showed once again that the experimental group scored higher than the comparison group (\(\bar{X} = 86.9, S.D = 4.8\); \(\bar{X} = 73.8, S.D = 6.2\); \(t = 25.04, P < 0.01\); see Table 1).

In sum, the results of the knowledge tests in both units confirm that students who learned with the TSC learning materials had significantly higher scores in a knowledge test compared to students who learned by traditional means.

Table 1. Comparison between knowledge scores in the experimental and comparison groups in two of the TSC units

<table>
<thead>
<tr>
<th>Unit</th>
<th>Experimental Mean grade</th>
<th>Experimental SD</th>
<th>Control Mean grade</th>
<th>Control SD</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic Revolution (argumenation skills)</td>
<td>72.9</td>
<td>6.0</td>
<td>59.4</td>
<td>4.1</td>
<td>3.94</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Water Balance in Living Organisms (Scientific and Critical thinking skills)</td>
<td>86.9</td>
<td>4.8</td>
<td>73.8</td>
<td>6.2</td>
<td>25.04</td>
<td>&lt;0.01</td>
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4. SYSTEMATIC ANALYSIS OF THE GENETIC REVOLUTION UNIT FROM THE PERSPECTIVE OF THE RELATIONSHIPS BETWEEN KNOWLEDGE AND THINKING

In order to demonstrate how the TSC learning activities can foster the growth of science knowledge let us examine in some depth selected examples of learning activities from the unit “Genetic Revolution—Discussions of Moral Dilemmas”. The goal of this unit is to foster students’ argumentation skills while teaching key concepts in genetics. The unit consists of ten learning activities that teach argumentation skills in an explicit way through bioethical dilemmas. The following argumentation skills are addressed: (a) the ability to formulate an argument; (b) the ability to provide supporting justifications; (c) the ability to offer an alternative argument; and, (d) the ability to rebut the alternative argument.

Between confronting the first and second dilemmas, one lesson was devoted to explicit instruction of argument structure, focusing on the differences between good and bad arguments (e.g., good arguments include true, reliable and multiple justifications; they also refer to alternative arguments and rebut them). Then, these skills were practiced throughout the program by several means: discussions between pairs of students, group discussions, whole class discussions and individual written assignments.

Each of the learning activities focuses around a moral dilemma regarding recent developments in genetics. Each dilemma includes questions that require knowledge of genetic concepts. Some of the dilemmas refer to concepts that are taught in the regular genetics curriculum (e.g., recessive versus dominant traits, X-linked traits and nature versus nurture). Other dilemmas refer to concepts that are not part of the regular curriculum (e.g., information about genetic traits and counseling, gene therapy and genetic cloning).

The introductory section of each dilemma includes a short teaching unit concerning the relevant genetic concepts. Students need to make use of their biological knowledge in order to think effectively about the dilemmas. The value of grounding decisions upon reliable knowledge is explicitly emphasized throughout the unit.

Implementation of the Genetic Revolution unit in schools was accompanied by an evaluation study. The goal of the study was to investigate students’ learning from two perspectives. The first perspective — acquisition of biological knowledge — is described in what follows. The second perspective — acquisition of argumentation skills — is described in the next chapter.

Subjects in this study were ninth grade students in two heterogeneous schools. As mentioned earlier, they were divided into two groups: experimental (N=99) and comparison (N=87). Students had learned basic concepts in genetics (e.g., phenotype, genotype, recessive and dominant traits, and Mendel’s first and second laws) as part of their science curriculum prior to the beginning of this study. All subjects learned additional, advanced concepts in genetics during this study. Students in the experimental group learned these concepts through the Genetic Revolution unit. Students in the comparison group learned these concepts by conventional methods: a special booklet was written, containing all the genetic information taught by the Genetic Revolution unit. The booklet presented this information in a traditional textbook approach. Teachers who taught the comparison group were instructed to teach it by first presenting that information and then asking students to solve relevant standard genetic textbook problems. Both groups studied these concepts for the same time (approximately 12 lessons). Examples of two dilemmas taught in this unit are presented in Figure 1.

Figure 1. Examples of two dilemmas

**Example #1 – The Cystic Fibrosis dilemma**

Cystic Fibrosis (CF) is an autosomal recessive genetic trait. It is one of the most prevalent genetic diseases. In England and the United States one out of 2000 newborns is affected and one out of 20 people is a carrier. Cystic fibrosis causes a deficient functioning of the external secretion glands that is pronounced (among other things) in the production of salty sweat, in digestion disorders, and in the production of large quantities of mucus in the respiratory tracts. The mucus causes recurrent lung infections. Each additional infection adds to the long-term damage to the lungs. The disease is therefore lethal: patients rarely survive past the age of 40.

The gene responsible for CF has been located. Scientists from laboratories in several countries are now working on methods for genetic therapy. One idea was to substitute a healthy gene for the deformed one in the lung tissue. However, the complex branching of the lungs makes it impossible to remove the Epithelium cells and then return them after the gene substitution. In 1992 one group of researchers succeeded in inserting the gene into the Epithelium of a rat’s lung where it continued to function for 6 weeks. Another research direction focuses on the development of a spray consisting of normal genes attached to transporters whose role will be to insert the genes into the cells. The idea is that patients will inhale the spray from time to time (with the hope that the normal genes will be able to function in the cells). Despite all these efforts, it is still a long way before genetic treatment of CF can become practical. Meanwhile, patients keep suffering.

Dilemma:

b1. What is the moral problem under consideration?

b2. Do you think they should perform an abortion? Offer reasons for your position!

b3. Your friend disagrees with you. Define his/her position. Offer reasons for that position (what might your friend say to convince you that s/he is right?)

b4. What will you answer your friend? Explain!
Example #2 - The Huntington dilemma

Huntington Disease - a ticking time bomb

Huntington Disease is a dominant genetic trait. Carriers of the affected allele will develop symptoms at some stage of their life. The typical age for onset of symptoms is between 35 and 45. Sick people develop involuntary tremors of the limbs and personality alterations: outbursts of crying, unexplained anger, memory loss and sometimes-schizophrenic behavior.

Severity of symptoms at various stages of the illness differs from one patient to another. It is a fatal disease. Death occurs around the age of 50. In their final years patients are in a vegetative state.

Please note: Huntington is a dominant (not recessive) trait. Still, patients are free until adulthood.

Case #1

Discuss the following dilemma in small groups. Each student should first clarify his/her own position and then discuss it with his/her peers. Please remember that the purpose of the discussion is to elucidate the issue by listening to each other and not to conduct a debate in which each participant tries to win.

Grandpa Henry became sick with Huntington disease at the age of 45. His condition deteriorated from day to day with much agony. His son, Jonathan, took care of him with great affection and sadly followed the decline in his condition. Grandpa Henry passed away when he was 51 years old. Miriam, Henry’s granddaughter, witnessed this painful process. Miriam is now 22 years old and is about to get married. She would like to be tested in order to find out whether or not she is a carrier of the disease. She wants to be able to decide how to plan her future: Should she invest several years in higher education, acquiring a profitable profession or should she travel around the world in order to enjoy the few good years she still has left. Should she have children, or perhaps give up that possibility?

Remember our rule: Before we can start thinking about ethical aspects of a dilemma, we must first understand the biological facts!

1. Because Huntington is a rare trait we assume that neither Grandma (Grandpa Henry’s wife) nor Miriam’s mother are carriers. According to the information you have, what are the chances that Miriam is a carrier?

   Jonathan, Miriam’s father, does not want to find out whether or not he is a carrier. He believes that if he were to discover that he will eventually become sick, this knowledge would destroy whatever good years he may still have. Jonathan therefore is opposed to Miriam getting tested.

2. Before formulating your position, please define the problem you must solve:
   a. Why doesn’t Jonathan want Miriam to be tested?
   b. If it turns out that Miriam is a carrier, what are her chances of giving birth to an affected child?
   c. Why does Miriam want to be tested?

   Usually, we recognize a person’s “right to know”. In this case a person’s right to know is in conflict with another person’s “right not to know”.

Please note: Our assumption is that Miriam cannot be tested while her father remains ignorant about the test’s results (i.e., suppose she plans to get married but says that she will cancel the wedding if she discovers that she is carrier. If she then cancels the wedding her father must necessarily realize that she is a carrier).

The reasons for that decision are:

<table>
<thead>
<tr>
<th>Miriam should decide to</th>
<th>Miriam should decide to</th>
</tr>
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<tbody>
<tr>
<td>a.</td>
<td>b.</td>
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</table>

Case #2

Gila is a 28-year-old woman who was recently married. Gila’s father is 50 years old. He has been sick with Huntington for the past five years. Initially, Gila did not wish to be tested in order to find out whether or not she carries the gene for Huntington disease. However, she then became pregnant and felt that she must find out whether her fetus is a carrier. The test showed that her fetus is indeed a carrier of the allele for Huntington disease.

Should Gila abort her fetus?

In order to demonstrate the relationship between the Genetic Revolution unit and students’ biological knowledge, two analyses were carried out. In the first analysis we demonstrate how genetic knowledge is integrated into a typical task. In the second analysis we demonstrate how students actually use genetic knowledge while they reason about a typical Genetic Revolution task.
5. THE INTEGRATION OF GENETIC KNOWLEDGE INTO A TSC TASK

An examination of the Huntington dilemma (see Figure 1) shows that its introduction consists of some biological information about Huntington Disease, emphasizing the fact that although Huntington is a dominant (and not a recessive) trait, patients are symptom free until adulthood.

This emphasis was added because of students’ common pre-conception that since dominant traits are invariably expressed in the phenotype they must be apparent at all times. Following this introduction, students are presented with three cases demonstrating the fact that Huntington symptoms break out only at adulthood, although the trait is dominant (only two of the three cases are described in Figure 1).

In discussing Case #1, students are explicitly reminded that before they can start thinking about the ethical aspects of a dilemma, they must first understand the pertinent biological facts. Questions 1 and 2a are similar to questions that may be found in many Genetics textbooks. However the fact that here they are embedded in the context of a dilemma may contribute to a more meaningful solving problem process. The content of the dilemma represents a case from the real world, which most students find intriguing. Rather than solving genetic problems in a disconnected way that is typical of textbooks, the answers to the genetic questions within the dilemmas are required here for making sense of a concrete case.

Students must once again rely on their biological knowledge in order to give a full answer to question 4 (What should Miriam do? Why should she do it?), because they have to think about Miriam’s chances of being a carrier and about her chances of giving birth to an affected child. By doing so, they process their biological knowledge at the level of application.

Although case #2 does not include similar explicit questions regarding the fetus’s chances of being a carrier, it includes such questions implicitly, because in order to justify their opinions students must once again carry out a genetic analysis and apply it’s findings. In addition, as they work through the dilemma, students encounter additional information about Huntington Disease. Similar considerations apply to all other dilemmas.

6. STUDENTS’ USE OF SPECIFIC GENETIC KNOWLEDGE IN CONSTRUCTING ARGUMENTS

The content analysis of the Huntington dilemma demonstrated how various issues that pertain to knowledge in genetics are integrated into the task. The dilemmas thus have the potential to induce application of biological knowledge as students work through them. But was this potential in fact realized? Did students actually use biological knowledge when they reasoned about the problems presented by the dilemmas?

This question was addressed through an analysis of students’ written responses to the first question in the Cystic Fibrosis dilemma. As can be seen in Table 2, following the presentation of the information about Cystic Fibrosis, students were asked to answer the following question:

a. Rebecca and Joseph got married and Rebecca is now pregnant. Should they abort the embryo? Explain!

<table>
<thead>
<tr>
<th></th>
<th>N (148)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No biological knowledge is considered</td>
<td>48</td>
<td>32.4</td>
</tr>
<tr>
<td>2. False consideration of biological knowledge</td>
<td>36</td>
<td>24.3</td>
</tr>
<tr>
<td>3. Consideration of non-specific biological knowledge</td>
<td>40</td>
<td>27.0</td>
</tr>
<tr>
<td>4. Correct consideration of specific biological knowledge</td>
<td>24</td>
<td>16.2</td>
</tr>
<tr>
<td>Total</td>
<td>148</td>
<td>100</td>
</tr>
</tbody>
</table>

7. COMPARING CONSIDERATIONS OF BIOLOGICAL KNOWLEDGE IN THE EXPERIMENTAL AND COMPARISON GROUP

The significance of biological knowledge for the construction of sound arguments is emphasized throughout the Genetic Revolution unit. Therefore, it is of interest to assess whether the program affected the extent to which students considered biological knowledge. The same question (i.e., “Rebecca and Joseph got married and Rebecca is now pregnant. Should they abort the embryo? Explain!”) was also given at the end of the unit, as part of post-test 2.
The analysis of the pre-test data presented in the previous section combined data from both the experimental and the comparison groups. When the pre-test data from the two groups were analyzed separately, no significant differences were found between the two groups.

However, when the post-test data from the two groups were analyzed separately three statistically significant differences were found (see Table 3): (a) the frequency of students who did not consider any biological knowledge was higher in the comparison group (30.4% versus 11.3% respectively);  
(b) the frequency of students who employed false consideration of biological knowledge was also higher in the comparison group than in the experimental group (16.1% versus 4.8% respectively); and (c) the frequency of students who considered specific biological knowledge correctly was higher in the experimental group than in the comparison group (53.2% versus 8.9% respectively). These results indicate that the Genetic Revolution unit contributed to students' awareness of the importance of specific biological knowledge in constructing arguments about this dilemma.

Table 3. Comparison between experimental and comparison group: Do students consider biological knowledge in the post-test?

<table>
<thead>
<tr>
<th></th>
<th>Experimental group</th>
<th>Comparison group</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>( N )</td>
<td>%</td>
</tr>
<tr>
<td>No biological knowledge is considered</td>
<td>7</td>
<td>11.3</td>
</tr>
<tr>
<td>False consideration of biological knowledge</td>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>Consideration of non-specific biological knowledge</td>
<td>19</td>
<td>30.7</td>
</tr>
<tr>
<td>Correct consideration of specific biological knowledge</td>
<td>33</td>
<td>53.2</td>
</tr>
<tr>
<td>Total</td>
<td>62</td>
<td>100</td>
</tr>
</tbody>
</table>

*\( P<0.05; **P<0.01; ***P<0.001 \)

8. SUMMARY: CONTENT AND THINKING IN THE TSC PROJECT

The essence of this chapter is to examine the linking of content and reasoning. Two tests were reported showing that students who learned science content by using the TSC learning materials gained higher scores in a knowledge test than students who learned by conventional means. These findings are limited in the sense that the two tests assess just knowledge rather than deep understanding. In other words, we did not compare the quality of students' knowledge, i.e., whether learning with the TSC learning activities improves the ability to apply the new knowledge in new contexts, to solve more complex problems or to retain it for longer periods. Nevertheless, these tests show that using the TSC learning activities not only maintains students' gains in a knowledge test compared to conventional methods but also actually improves it.

From an educational point of view this is one of the most significant findings from our research because it can be used to hold off common oppositions to the project. Like the teacher who was quoted in the introduction, opposition to teaching thinking according to the infusion approach often focuses on the issue of science knowledge. On numerous occasions in which I presented the TSC project, opponents stated that although they believed teaching thinking is indeed an important goal, we must not forget that dissemination of science knowledge and preparing students for standardized tests is science teachers' chief responsibility. Although I do not share this opinion because I believe that science literacy is beyond acquisition of facts, and that scientific generative knowledge can only be achieved through instruction that highlights thinking, the findings from these knowledge tests provide powerful arguments for this debate. I presented these findings on several occasions to convince teachers, principals and parents to support the thinking project, even in cases where there was no time or appropriate resources to explain the deep relationships between thinking and meaningful learning that are so abundant in the literature.

There are several possible explanations (not mutually exclusive) for the gain we found in students' knowledge. Instead of engaging science concepts by cognitive operations that consist mostly of recalling information, students engage the scientific concepts through higher-order cognitive operations. The examples of classroom episodes described throughout this chapter demonstrate how processing science content through tasks that involve thinking may contribute to knowledge construction, because the learning activities require students to perform complex mental operations within the science concepts that they learn. Such operations enable them not only to memorize these concepts but also to actively build mental representations, new relationships and personal understandings.

However, due to the pedagogies used in the TSC project other explanations for students' knowledge gains cannot be ruled out. Addressing the genetic concepts from the perspective of the social and moral dilemmas in the Genetic Revolution unit for instance, creates "anchored instruction" (see Bruer, 1993, for review). That is to say, these socially situated issues offer an "anchor" for learning, generate interest and connect to students' out-of-school life experiences. In addition, diverse instructional means were used throughout the project. Most lessons were not teacher-centered in the sense that for a substantial amount of the time students worked individually or in pairs and/or in small groups. Consequently, students' learning was rich in social construction of knowledge (see Duffy & Cunningham, 1995; Duit & Treagust, 1998, for review), in inquiry and in problem solving. According to the TSC approach such instructional means cannot be separated from teaching thinking. All of these means are known in the literature to induce gains in students' knowledge. Therefore, although it makes sense that the tight combination of content and thinking in the TSC activities are a plausible explanation for students' knowledge gains, it should be noted that this explanation had not been proved.

This note calls attention to a serious limitation of the research about the effectiveness of teaching thinking. In cognitive laboratory experiments, various teaching variables (i.e., the combination of content and thinking and of additional
pedagogical means such as group work, class discussions or active learning) may perhaps be separated in order to investigate their separate effects. However, in real classrooms it is difficult to conceive of a way for teaching thinking appropriately, without applying the pedagogies we have used in the present study and without violating students' right to good education. Ethical and educational considerations make it difficult to imagine a school that would introduce thinking activities, but would not allow children time to think for themselves or to express their ideas. Therefore, it is hard to imagine how future research might actually control these variables and provide empirical evidence for the relative contribution of each teaching variable to students' overall gains. It seems that the investigation of the effects of teaching thinking must be a package deal that includes thinking tasks and activities but also a variety of pedagogical means that characterize good teaching of thinking tasks.