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Designed-Based Research

▶ Evidence-Based Practice in Science Education

Designing and Assessing Scientific Explanation Tasks

Joseph Krajcik[1] and Katherine L. McNeill[2]
[1]CREATE for STEM Institute, College of Education and College of Natural Science, Michigan State University, East Lansing, MI, USA
[2]Boston College, Lynch School of Education, Boston, MA, USA

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The goal of science is to explain phenomena, reoccurring natural events that happen in the world. As such, scientists strive to understand how and why phenomena occur. All explanations begin with a need to find an answer to a question. A claim is frequently made in response to a question. In order to test these different claims, scientists often design and carry out investigations that allow them to collect data or they may use data that already exists. Scientists also use theoretical ideas to provide justifications for why the evidence supports or refutes these various claims. In constructing these explanations about the natural world, scientists engage in argumentation in which they debate competing claims by evaluating the validity of those claims and the supporting evidence. Here is where evidence and scientific principles play an important role. In science, the claims that best fit with the available evidence and scientific principles move forward in the community. When new evidence emerges that the claim cannot account for, claims are revised, producing a new explanation. As the Framework for *K-12 Science Education* argues, "Deciding on the best explanation is a matter of argument that is resolved by how well any given explanation fits with all available data, how much it simplifies what would seem to be complex, and whether it produces a sense of understanding" (NRC 2012, p. 68). The focus of the framework (NRC 2012) and the Next Generation of Science Standards (NGSS 2013) is for students to construct explanations based on evidence and scientific ideas.

To support students in constructing scientific explanation, McNeill and Krajcik (2011) suggest using a framework that consists of a claim, evidence, reasoning, and rebuttal. The framework supports students in constructing and critiquing explanations. The claim, evidence, reasoning, and rebuttal framework (CERR for short) can be used to develop explanation assessment tasks as well as analyze student explanations. The framework was adapted from Toulmin's (1958) work on argumentation. In writing explanations,

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students propose claims and support those claims with evidence and reasoning that provides a justification for that link between the data and the claim. They also need to argue why other claims don't fit the evidence as well as the claim they put forth, which is where the rebuttal frequently is incorporated.

The claim is a statement that expresses the answer or conclusion to a question or problem. When a question is posed, information is sought to provide evidence and justification for the claim or an investigation is planned to provide evidence to support the claim. As such, constructing an explanation can engage learners in other scientific practices such as designing investigation, analyzing and interpreting data, and arguing form evidence.

The other components of the scientific explanation framework provide the support and backing for the claim. A central feature of science is its use of scientific data as evidence to understand the natural world (National Research Council 2007). Evidence is scientific data that provided support for the claim. Data can come from observations and measurements from natural settings or from the results of controlled experiments. When constructing explanations, data can either be first or second hand. Firsthand data is data collected and generated by investigations planned by the experimenter. Secondhand data was collected and generated from investigations planned and conducted by other researchers. The accuracy or reliability of scientific data is often checked through multiple trials or by comparing different types of data. Students can either collect data themselves or be provided with data such as data tables, readings, or a database.

There needs to be appropriate and sufficient data to justify the support of a claim. Appropriate data need to be scientifically pertinent and important for supporting the claim. Sufficient data means that enough data has been generated and gathered to support the claim. Typically in science, we collect, analyze, and use multiple pieces of data to answer a particular question or problem.

Reasoning provides a justification that shows a way the data can be used as the evidence to support the claim. The reasoning states why the evidence supports the claim, providing a logical connection between the evidence and reasoning. Reasoning also requires discussing appropriate scientific principles to justify why the data can be used as evidence to support a particular claim. In explaining phenomena, there are multiple plausible explanations for how or why a phenomenon might occur. Often scientists need to provide an argument about which claim is the most appropriate. The rebuttal provides evidence and reasoning to rule out other possible alternative claims and provides evidence and reasoning for why the alternative is not the appropriate explanation for the question or problem. Scientists consider and debate these multiple possible claims.

Construction Scientific Explanation Tasks: How can you design and evaluate tasks to assess students' abilities to construct scientific explanations? How can explanation assessment tasks be designed to align with the key science ideas? Designing and judging assessment tasks that focus on scientific explanations will assess students' understanding of the structure of scientific explanations and disciplinary core ideas (NRC 2012). The claim, evidence, reasoning, and rebuttal framework provides structures for designing and assessing explanation tasks. McNeill and Krajcik (2011) and Krajcik et al. (2008) propose a process for developing scientific explanations assessment tasks. The process consists of seven steps:

Step 1: Identifying and unpacking the science ideas
Step 2: Selecting the level of complexity of the task
Step 3: Developing performance expectations
Step 4: Constructing the assessment task
Step 5: Reviewing the assessment task
Step 6: Using the base rubric to develop a specific rubric

Selecting and Unpacking Science Ideas: The first step entails selecting and unpacking the science ideas. National or state documents that specify what learners should know and that target disciplinary core science ideas addressed in the classroom can be used for selecting the science ideas. Examining documents and selecting the appropriate science ideas can help determine what specific science ideas are key for building scientific understanding necessary for problem solving and explaining phenomena.

After selecting the science idea, the ideas need to be "unpacked." Unpacking has two components. First, a science standard often contains many different science ideas. In order to develop a thorough understanding of the standard, it helps to break it down into related science ideas and to clarify each science idea in terms of its meaning and relationship to the other ideas. Second, it also helps to consider common student nonnormative ideas or challenges in learning the science ideas. The unpacking process helps to clarify what science ideas to target in the item as well as common student difficulties to incorporate into the item.

Selecting the Level of Complexity: The next step in designing scientific explanation assessment tasks is to select the level of complexity. Here, a decision on the level of complexity of the framework as well as difficulties students might experience when constructing explanations needs to be made. Level of complexity refers to the number of components and variations in those components that students will need to incorporate when responding to the task. Students could respond to only the first three components (e.g., claim, evidence, and reasoning), or the fourth component of rebuttal could also be included. Next, the level of difficulty for each component needs to be decided. Typically, the claim is at the simplest level.

Usually, the variation in the difficulty of the components occurs in varying the complexity of the evidence and reasoning. The amount of evidence and reasoning can vary from simple to complex. At the simple level, the evidence supports the claim, and at the moderate level, evidence that is appropriate and sufficient needs to be given. At the complex level, multiple pieces of sufficient and appropriate evidence need to be provided. Reasoning at the simple level provides a justification to support the claim and at the moderate level a justification of why the data can be used as evidence to support the claim using appropriate scientific principles. At the complex level, reasoning requires a justification of why the data can be used as evidence to support the claim using appropriate scientific principles for each piece of evidence. The rebuttal is only appropriate at the complex level and requires that counterevidence and reasoning be given to argue why possible alternative explanations are not appropriate. (See McNeill and Krajcik (2011), for a more complete description.)

Creating Performance Expectations: A performance expectation specifies a learning goal beyond the content knowledge that students are to learn by specifying how they will apply the science ideas (Krajcik et al. 2008; NRC 2012). In this respect, performance expectations specify how students will make use of the science ideas. Although a variety of active verbs can be used to describe how students will use science ideas, the use of scientific and engineering practices – designing an investigation, analyzing and interpreting data, constructing scientific explanations, arguing from evidence, and building models (NRC 2012) – specifies learning goals and what is hoped students will do in terms of important capabilities in science. This discussion focuses on the practice of constructing scientific explanations; however, the construction of other types of assessment tasks can use this process for developing a variety of assessment types.

A performance expectation is developed by crossing the scientific practice of explanation with a science idea of interest. Figure 1 shows a representation and gives an example of this process. Developing performance expectations provides explicit statements of learning goals that guide the design of learning tasks, assessment tasks, and the associated rubrics. Notice that in Figure 1, the performance expectation clearly states the expectations for the claim, evidence, and reasoning. The performance expectation specifies the science idea and how learners should use that knowledge, in this case constructing an evidence-based explanation about pure substances having characteristic properties. The performance expectation specifies the complexity of the evidence and reasoning that needs to be included in the assessment task.

Practice	Science idea from the framework for K-12 science education (NRC 2012)	Performance expectation
Scientific explanation	Each pure substance has characteristic physical and chemical properties (for any bulk quantity under given conditions) that can be used to identify it	Develop a scientific explanation with a claim that a pure substance has characteristic properties, two pieces of appropriate and sufficient evidence and reasoning that a substance has the same molecular composition and structure throughout and that other substances with different properties do not have this same structure and composition

Designing and Assessing Scientific Explanation Tasks, Fig. 1 Creating performance expectations. Scientific practice crossed with science idea to make a performance expectation

Sample	Density	Color	Mass	Melting point
1	1.0 g/ml	Clear	6.2 g	0.0 C°
2	0.89 g/ml	Clear	6.2 g	38 C°
3	0.92 g/ml	Clear	6.2 g	14 C°
4	0.89 g/ml	Clear	10.6 g	38 C°

Designing and Assessing Scientific Explanation Tasks, Fig. 2 Assessment task aligned with performance expectation. John measured the properties of several materials described in the data table below. He was confused because three of the samples had the same mass but different melting points and density. Using the data in the table, write a scientific explanation about whether any of the samples are the same substance. Make sure you include a claim, at least two pieces of evidence, and reasoning to justify your position

Developing the Assessment Task: Developing performance expectations provides specifications for constructing assessment tasks or learning activities to meet performance expectations. Performance expectations help to develop alignment among learning goals (the performance expectation), the learning tasks, and the assessment tasks. Figure 2 provides an assessment task that aligns with the performance expectation in Figure 1.

In writing the assessment task, identification of a context that is accessible to learners must also be taken into consideration. The context includes determining the phenomenon addressed in the task and the data students analyze and interpret to justify their claim. An appropriate context makes the task accessible to students. The assessment task in Figure 2 provides a phenomenon and science ideas that are accessible to middle school learners. The context also is important because scientific explanations are written to makes sense of specific phenomenon. In the example in Figure 2, it is about properties of a specific substance.

The task in Figure 2 would require middle school students to make the claim that samples 2 and 4 are the same substance because they have the same density and melting points. Their reasoning would include that density and melting point are properties that don't change with the amount of sample. The students would also need to specify that the reason why the density and melting points are the same regardless of amount is because the samples are made of the same types of molecules throughout both samples. Samples 1 and 3 are not the same substance even though the samples have the same mass because mass is not a characteristic that can be used to identify a sample as one type of substance or another. In responding to this item, students also have to engage in interpreting data; as such, this task engages students in a secondary scientific practice of data interpretation.

Review the Assessment Task: Assessment tasks need to be reviewed to check if the science ideas specified in the task are necessary and sufficient for responding to the tasks. The task also needs to be reviewed to assure that the assessment task is comprehensible to learners. The Project 2061 assessment evaluation framework (DeBoer 2005) provides an appropriate process for accomplishing this step. The Project 2061 assessment framework focuses on three criteria: necessity, sufficiency, and comprehensibility. Answering three questions focuses the review:

1. Is the knowledge necessary to correctly respond to the task?
2. Is the knowledge sufficient by itself to correctly respond to the task or is additional knowledge needed?
3. Is the assessment task and context likely to be comprehensible to students?

The necessity criterion examines if students need to apply the science ideas and the scientific practice intend by the assessment task to appropriately respond to the item. In many respects, unpacking the science ideas and specifying the performance expectation helps to ensure if the science ideas and scienttific practice are necessary to provide a response to the item.

The sufficiency criterion considers what other science ideas or scientific practice is included in the assessment task and if that additional knowledge is appropriate to include. As such, the sufficiency criterion provides a check if other science ideas or scientific practices go beyond those specified in the learning goal. If the assessment task includes science ideas or scientific practices that the learners have not developed, then learners are likely to respond inappropriately to the item not because they don't have an understanding of the target goals but because they don't know these additional science ideas or practices used in the task. If learners have previously studied this additional content, it might be appropriate to include. For instance, to respond appropriately to the assessment task in Figure 2, students also need to know that density and melting point are properties of a substance but that mass is not a property of a substance. They also need to know how to read a table and interpret the data in the table. The additional science ideas and the level of data interpretation are appropriate for middle school science.

The comprehensibility criterion considers if the assessment item is appropriately written to meet the experiences and background knowledge of the learners. In the section on developing the assessment task, the appropriateness of the phenomena and science ideas were considered. In determining if the assessment task and context are likely to be comprehensible to students, students' cultural backgrounds and the literacy demands of the task also need to be taken into consideration. If the reading demands are beyond those of the students, the students might know the target learning goals but respond inappropriately because of the language. Consideration of cultural backgrounds is essential as learners from various backgrounds could have difficulty interpreting the context of an assessment task.

Using the Base Rubric to Develop a Specific Rubric: A base explanation rubric (see Appendix 1) provides a general rubric for evaluating scientific explanations for various science ideas (McNeill et al. 2006; McNeill and Krajcik 2011). The base rubric includes the four components of a scientific explanation and provides guidance about developing different levels of student achievement for each of those components in a specific rubric. The specific rubric combines both the general structure of a scientific explanation and the appropriate science ideas and evidence for the particular task. Adapting a base rubric to develop a specific rubric involves aligning the rubric to a particular assessment task. The specific rubric is designed to a particular explanation task and shows what science ideas and evidence the students needs to apply at each level of achievement. The specific rubric includes determining what would count as an appropriate claim, evidence, and reasoning. When applicable, it also needs to include specifying the alternative explanations and the evidence and reasoning to support refuting the alternative claims. To develop a specific rubric, begin by using the base rubric and constructing the ideal student response for each component.

Summary Statement: To support students in constructing scientific explanations, McNeill and Krajcik (2011) suggest using a framework that

Designing and Assessing Scientific Explanation Tasks, Appendix 1 Base Explanation Rubric

	Level		
Component	0	1	2
Claim: A response to the original question	Does not make a claim, or makes an inaccurate claim	Makes an accurate but incomplete claim	Makes an accurate and complete claim
Evidence: Scientific data that supports the claim. The data needs to be appropriate and sufficient to support the claim	Does not provide evidence, or only provides inappropriate evidence (Evidence that does not support claim)	Provides appropriate, but insufficient evidence to support claim. May include some inappropriate evidence	Provides appropriate and sufficient evidence to support claim
Reasoning: A justification that links the data to the claim. Reasoning shows why the data counts as evidence by using appropriate and sufficient scientific principles	Does not provide reasoning, or only provides reasoning that does not link evidence to claim	Provides reasoning that links the claim and evidence. Repeats the evidence and/or includes some scientific principles, but not sufficient	Provides reasoning that links evidence to claim. Includes appropriate and sufficient scientific principles
Rebuttal: Communicates possible alternative explanations and provides evidence and reasoning for why the alternative explanation is not appropriate	Does not communicate alternative explanations exist or makes an inaccurate rebuttal	Communicates alternative explanations and provides appropriate but insufficient evidence and reasoning in making the rebuttal	Communicates alternative explanations and provides appropriate and sufficient counter evidence and reasoning when making rebuttals

Adapted from McNeill and Krajcik (2011)

consists of a claim, evidence, reasoning, and rebuttal. The framework assists students in constructing and critiquing explanations as well as supports teachers and designer in designing explanation learning tasks and explanation assessment items. In writing explanations, students propose claims and support those claims with evidence and reasoning that provides a justification for that link between the data and the claim. They also need to argue why other claims don't fit the evidence as well as the claim they put forth. A six-step process that begins with identifying and unpacking key science ideas and ends with developing a specific rubric provides a technique for developing explanation assessment items that align with the target core science ideas and will help ensure that assessment items are appropriate for the background experiences and prior knowledge of students.

Cross-References

▶ Argumentation Environments
▶ Assessment of Doing Science
▶ Assessment of Knowing and Doing Science
▶ Formative Assessment
▶ Inquiry, Assessment of the Ability to
▶ Summative Assessment

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Designing and Assessing Scientific Modeling Tasks

Kristin Mayer[1] and Joseph Krajcik[2]
[1]CREATE for STEM Institute, College of Education, Michigan State University, East Lansing, MI, USA
[2]CREATE for STEM Institute, College of Education and College of Natural Science, Michigan State University, East Lansing, MI, USA

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Scientists strive to provide causal accounts that explain and predict phenomena. Scientists use models to represent relationships among components to test and explain complex phenomenon. As such, modeling is an integral and common practice across the science disciplines. Scientists continually form, test, evaluate, and revise models to explain and predict phenomena. By testing models against data, scientists evaluate and revise models to better fit the data. When a model can no longer account for the data, the model is revised.

> Observations of the natural world motivate the construction of models, which in turn motivate further observations and drive the resulting interpretations. In this way, models become explanations: that is, stipulations of possible cause and effect relations in the phenomenon under investigation. (Penner et al. 1998, p. 430)

Defining Scientific Modeling

The practice of scientific modeling differs significantly from the way models are often thought of and talked about in everyday life. For example, a model airplane is usually a smaller version of an actual plane. In this colloquial use of the word, a model is a scale representation of an object. However, scientific modeling is more complex and abstract process. A scientific model does include representations, but it does not it is representing. A model may include invisible components including symbols to indicate the relationships among the components of the model. Although scientific modeling can include representations that look similar to the system that is being modeled, it can also include mathematical representations, graphs, and computer simulations.

All models need to explain and predict phenomena and be consistent with scientific theory; in other words, the model must help explain what, how, or why a phenomenon occurs. Moreover, models need to specify the relationships among components in the system that is being explained to provide a causal account. Scientific modeling is also an iterative process. A scientist will create a model to explain a phenomenon. The model is then used to make predications about related phenomena. Those predications are tested and used to revise the model. The model is refined to design a more robust explanation. The model continually evolves with additional evidence.

One model will not be able to capture all aspects of a phenomenon. In fact, models often simplify the system in order to highlight certain aspects. Thus, different models may be needed to explain different aspects of one particular phenomenon. For example, a lightning strike is a complex phenomenon. One model could highlight movement of particles in the air to explain how large charges build up in thunderstorms. Scientists would use another model to explain why light and sound are observed when the lightning strikes. A different model is needed to predict the likelihood that certain weather systems will lead to lightning strikes. Finally, scientists would use a mathematical model to triangulate locations of strikes using information about where and when they were observed. Scientific modeling is a complex process that requires analyzing a variety of evidence and utilizing theory to explain and predict phenomena.

Modeling in Science Classrooms

Scientific modeling is one of the scientific practices identified in the Framework for K-12 Science Education that should be used in conjunction with disciplinary core ideas and crosscutting concepts to help learners form usable understanding of science (National Research Council 2012). The various scientific practices work together to help build our understanding of the world. For instance, scientists often argue that one model better fits the data than another model. Although developing and using models is central to the practice of science and as such should be an important aspect of what occurs in science classrooms, developing, testing, and revising models are seldom seen in the science classroom.

The models that students develop are concrete artifacts that can be shared and critiqued by others. These artifacts provide a window into students' mental models or their understanding of this area. When students develop and test models to explain and predict phenomena, the process of developing models helps learners form integrated conceptual understanding. Integrated conceptual understanding refers to concepts and connections that students hold and use to represent and explain his or her understanding of phenomenon in the world. Models can be drawings, three-dimensional structures, a set of equations, qualitative descriptions, or a simulation.

Supporting Students in Building Models

Due to the complex nature of the practice of scientific modeling, teachers and curriculum designers need to support students in the process by providing criteria for developing a scientific model. Although models are used in a variety of ways, there are similar elements across models:

1. Identification and specification of the components or variables important for the analysis of the system.
2. Description or representation of the relationships or interactions among the components or variables.
3. The collection of relationships provides a causal account of the phenomena under study.

Even a mathematical model includes these elements. For example, $F = ma$ includes variables to represent the amount of force, mass, and acceleration of an object or system of objects. The equation indicates several relationships among these variables. Finally, the equation serves as a model, when it provides a causal account of the phenomena. The equation alone is a simple algebraic statement; however, it serves as a model if it is used to explain observations or make predictions about the motion of one or more objects.

Designing Assessment Tasks for Scientific Modeling

The Framework for K-12 Science Education (NRC 2012) and the Next Generation Science Standards (Achieve 2013) define science learning expectations as the blending of scientific practices, crosscutting concepts, and disciplinary core ideas to form performance expectations. A performance expectation defines knowledge in use. Assessing scientific modeling requires the use of scientific ideas. A performance expectation for modeling is developed through crossing the practice with disciplinary core ideas and crosscutting concept. Finally, a relevant phenomenon is added so the performance expectation will lead to a rich assessment task.

Clear and specific performance expectations provide guidance in writing an assessment task as they point out important elements that need to be included in the assessment. Table 1 shows an example of a performance expectation. The performance expectation shown in Table 1 contains two critical elements: (1) the scientific practice of developing a model and (2) the use of a disciplinary idea – the structure of an atom. This specificity supports the alignment between the performance expectation and the assessment task. Figure 1 shows an assessment task that aligns to the performance expectation in Table 1. The performance expectation and assessment task are appropriate for ninth or tenth grade physical science.

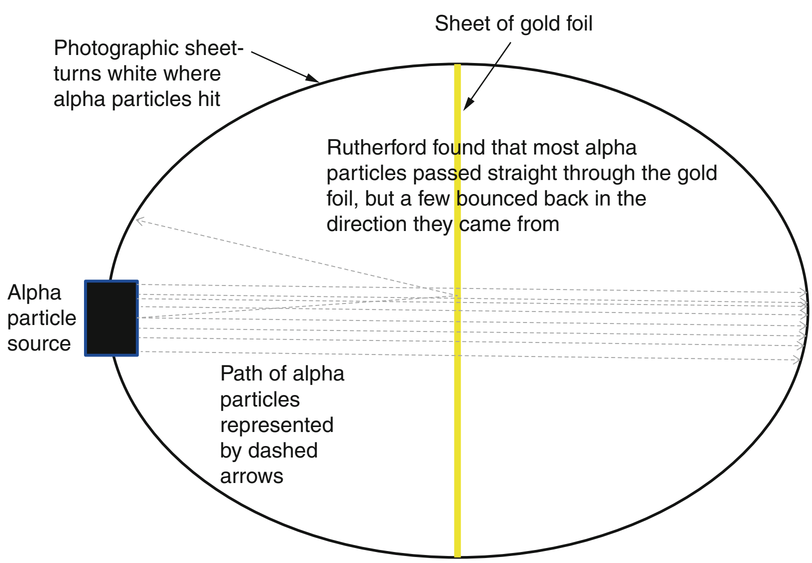
Designing and Assessing Scientific Modeling Tasks, Table 1 Defining performance expectation for modeling

Scientific practice: developing and using models	Disciplinary core idea: "Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons" (NRC 2012, p. 107)	Relevant phenomena: Rutherford observed that when alpha particles were shot at a thin sheet of gold foil, most of the particles passed through mostly unaffected, but a few returned close to the direction from which they came	Performance expectation: Develop a scientific model for atomic structure that can account for experimental results related to the structure of the atom

Note that the assessment task requires that students explain in writing how their model is related to the phenomenon; a diagram alone cannot fully assess all key elements of a model and if students demonstrate understanding of the performance expectation.

Assessing Student Responses

Base Modeling Rubric: A base, modeling rubric provides a general rubric for evaluating scientific models that explain a variety of phenomena. The base rubric includes the three elements of a scientific model and provides guidance about assessing different levels of student achievement



Draw (or revise) your model of atomic structure	How does this model explain Rutherford's observations?

Designing and Assessing Scientific Modeling Tasks, Fig. 1 An assessment task. When Rutherford shot positively charged alpha particles at a thin sheet of gold atoms, he observed that most of the particles passed straight through but was surprised to see some that returned to the direction they came from

Designing and Assessing Scientific Modeling Tasks, Table 2 Base rubric for assessing scientific models

	Levels		
Criteria	0	1	2
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image of the phenomenon	Model may include both visible and invisible components, but may be missing key components, or components are not clearly labeled leaving uncertainty in the interpretation of the model	Model highlights all necessary components, including both visible and invisible, that are needed for explaining the phenomena. All components are clearly labeled or identified in description
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Model is either missing key relationships or includes some inaccurate relationships between component	Model includes all appropriate relationships necessary for the explanation of the phenomena
The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	Model is not used to explain phenomena	Model is used to try to explain phenomena, but there are some inaccuracies in the explanation of the phenomena	Model is consistent with available evidence and is used to explain phenomena

for each of the elements. Table 2 provides a general base rubric for assessing students' scientific models.

Developing Specific Rubrics: A specific rubric combines both the general structure of scientific models with the appropriate science ideas and evidence with a particular assessment task. Adapting a base rubric to develop a specific rubric involves aligning the rubric to a particular assessment task. The specific rubric includes determining what would count as appropriate components and relationships in the specific task. To develop specific rubrics, begin by using the base rubric and constructing the ideal student response for each element (Modified from McNeill and Krajcik 2008).

To develop the specific rubric for the Rutherford task, the specific components, relationships, and the connection to the phenomenon need to be identified. Note that these specifics are being defined with respect to the instructional methods used to cover the material in class. In this example, the students learned about Rutherford's gold foil experiment using a simulation where students manipulated the concentration of the positive charges and observed the effect on the electric field and motion of the positive alpha particles. This simulation can be found at http://concord.org/tst/rutherford-model.

Step 1: Identify the object/components: what components need to be specified. The key components needed to explain the results of the Rutherford observations include protons and alpha particles. Additionally, it is necessary to include that these particles are all positively charged. Further, the strength of the electric field around the protons is an important invisible component for explaining how the path of a few of the alpha particles changed so drastically.

Step 2: Specify the specific relationships: what relationships need to be specified. In the Rutherford example, there are two important relationships to include. Since the alpha particles and protons are all positively charged, these particles will repel. An additional relationship that is relevant for explaining Rutherford's observations is the connection between the strength of an electric field and the concentration of charged particles. The electric field is stronger around concentrated charges.

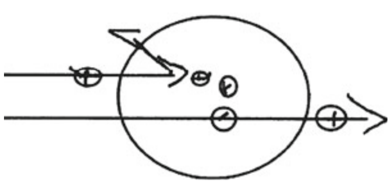
Step 3: Show the connections among the relationships. Do the connections among the

Designing and Assessing Scientific Modeling Tasks, Table 3 Specific rubric for assessing Rutherford modeling task

	Levels		
Criteria	0	1	2
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image representing the outcome of Rutherford's gold foil experiment	Model may include both visible and invisible components, but may be missing key components, or components are not clearly labeled leaving uncertainty in the interpretation of the model. Model may not indicate the charge of particles	Model highlights protons and alpha particles and identifies these particles as positively charged
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Model is either missing key relationships or includes some inaccurate relationships between component	Model includes repulsive forces between positively charged alpha particles and protons. Model includes relationship between concentration of protons and strength of electric field
The collection of relationships provides a causal account of the phenomena: Model is used to explain or predict a phenomenon or specific aspects of a phenomenon	Model is not used to explain phenomena	Model is used to try to explain phenomena, but there are some inaccuracies in the explanation of the phenomena	Model is consistent with and used to explain the evidence from Rutherford's experiment that most of the alpha particles pass straight through the gold foil but a few are deflected at a large angle

Atomic model to explain Rutherford's observations from the gold foil experiment

Student's representation



Transcript from interview:
This is like the atom and inside of it is both the positive and the-protons and electrons, and when you send out, [an alpha particle] um one woulde either bounce off or go right through depending on what its charge was.
If the alpha particle hits a proton, it will be reflected because they repel; if it hits an electron, it would come right straight through

Designing and Assessing Scientific Modeling Tasks, Fig. 2 Student atomic model to explain Rutherford's observations

relationships provide a causal account for why the phenomenon occurs? Rutherford observed that a few of the positively charged alpha particles returned almost in the direction they originally came from. In order to change the path of the alpha particle this drastically, there must be regions with highly concentrated positive charges. However, the majority of the alpha particles passed almost unaffected through the gold foil. Thus, inside the gold atoms, there must be regions with highly concentrated protons and large regions without protons.

Adding these specifications to the base rubric shown in Table 2 develops the specific rubric. Table 3 displays an example of a specific rubric that would be used to assess students' responses to the task described in Fig. 1.

Example of Assessing Student's Model: Figure 2 provides an example of a student's representation of atomic structure and her

Designing and Assessing Scientific Modeling Tasks, Table 4 Evaluation of sample student model

Criteria	Evaluation	Description
Components	Level 2	Student included protons and alpha particles. Though these are not explicitly labeled in the diagram, the student identified them in the description of the model during the interview. The protons and alpha particles are all labeled with plus signs indicating they are positively charged
Relationships	Level 1	Student included repulsive forces between the alpha particles and protons. However, the relationship between the concentration of positive protons and the strength of the electric field is missing. Instead, the student relates the path of the alpha particles to the interaction with individual particles rather than electric fields created by collection of particles
Connection to phenomenon	Level 2	The student used the model to explain how some alpha particles were reflected and others passed through. Though the student had an inaccuracy in that she related the path of the alpha particles to individual particles rather than a collection of particles, this inaccuracy was captured in the evaluation of the relationship category. The student's description of the phenomenon is accurate and the model provides a causal account to explain the phenomenon

description of how the model related to the phenomenon. The assessment task here is a bit different than the task described above. The students drew representations of atomic structures and then were interviewed about the representations and how they related to a variety of phenomena. The example is provided to illustrate the connection between the base rubric, specific rubric, and a specific example. The example includes the representation the student drew, a selection of the transcript from the interview, and an evaluation of the model using the rubric.

Overview of the analysis of the student model: The model includes appropriate components. Plus and minus signs indicate the charges of the various components. Arrows show a relationship between alpha particle and the path of the alpha particle depending if it interacts with a proton or not. However, the model includes inaccurate ideas: The student's model has alpha particles interacting with an individual proton or electron rather than with the strong electric field due to a concentration of multiple protons. Table 4 displays an evaluation of this student's model based on the criteria described in the base and specific rubrics.

Summary Statement

Scientific modeling engages learners in a complex and essential scientific practice. Teachers need to support students in developing and revising models. This includes providing a structure to develop and evaluate student's models. This structure also helps students to evaluate and revise their own models as they gather additional evidence. Due to the complex nature of the practice of scientific modeling, it is important to describe the three elements of the model to evaluate the components included in the model, relationships between these components, and the connection among the components and relationships in the model to give a causal account of why the phenomena occurs. Additionally, because models explain or predict phenomena, it is important to write assessment tasks that ask students to connect their models to phenomena. Rubrics can monitor students developing conceptual understanding as students continue to build and refine their evolving models. The analyses of students' models provide insights into students' integrated conceptual understanding.

Cross-References

▶ Argumentation Environments
▶ Assessment of Knowing and Doing Science
▶ Formative Assessment
▶ Inquiry, Assessment of the Ability to
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Developmental Perspectives on Learning

Terry Russell
Centre for Lifelong Learning, University of Liverpool, Liverpool, UK

Human curiosity to understand the immediate world and wider universe we inhabit generates a legacy of cultural capital for succeeding generations. Cumulative as well as revolutionary insights spawn a body of knowledge in the form of artifacts, information and communication formats, and centers of research populated by living human expertise. Into this context arrive about 250 births per minute across the world. What do we know about the induction of these new arrivals to the frameworks science offers for making sense of the world? How and where should we begin the enterprise to shape the unknowing dependence of neonates toward scientific literacy for all and a more single-minded commitment for some?

The scientific study of intellectual growth from infancy to maturity is a relatively recent discipline, propelled in the early twentieth century by major contributions from Piaget and Inhelder in Geneva and Luria, Vygotsky, and their circle in the Soviet Union. While the former focused on the developmental construction of knowledge (genetic epistemology) as a "natural" process of intellectual adaptation, independent of instruction, the latter prioritized sociohistorical enculturation processes, especially as mediated by language, with teaching and learning a preeminent interest. Vygotsky's introduction of the term "zone of proximal development" (readiness for the next jump in learning) into educational vocabulary remains important in considering progression.

A number of major disciplines inform thinking about progression in children's developing science-relevant capabilities: cognitive-developmental psychology and curriculum studies complement and supplement science knowledge. The trend in such research has been to extend inquiries to increasingly younger age groups (including pre-birth studies by psychologists) and, on the part of curriculum researchers, an interest in "emergent science" in children from about age three onward. Recent decades have also brought dramatic social contextual changes in the technologies of information and communications environments to which infants and young people in many societies are exposed. This social change is linked to a strong prevailing value position in liberal democracies, manifest in the promotion of attitudes and behaviors consistent with an expectation that, from a very early age, learners should show curiosity and be exploratory, autonomous seekers and evaluators of information. Notwithstanding the enormous body of existing scientific knowledge, active assembly of knowledge is valued by educators, rather than passive receipt of transmitted information. The implication is that a judicious ordering and scaffolding of the salient experiences to be negotiated by learners is essential to achieve a regulated, cumulative progression.

While a senior school and later adult science education specialism may apply to only a minority of students, the underpinning cognitive, affective, and social skills that comprise essential antecedent capabilities to a mature scientific literacy can be identified and nurtured from a very young age. Three aspects describe most of the important foundations for the development of scientific literacy: ideas together with the evidence to support them;

scientific inquiry skills (including variable handling), sometimes referred to as "procedural understanding"; and conceptual development, in the form of knowledge and understanding of the subject matter of science.

Progression with Ideas and Evidence

The area of ideas and evidence – that is, having ideas about what entities exist, how they might be classified, and how such beliefs are justified – has pervasive relevance across the curriculum and as a life skill but is quintessentially important to scientific thinking. While independence of thinking is valued in science, particular times and cultures frequently exert pressure to conform to prevailing beliefs, whether fueled by precedent, folk knowledge, superstition, or simply the weight of orthodoxy (as Galileo's experience confirms most dramatically).

Constructivist research conducted in recent decades confirms that children have ideas, but need an accepting ambience in which to express them. By engaging in a dialogic process, they may gain confidence and be empowered to take ownership of their learning. However, as well as overcoming reticence, the emergence of a "theory of mind" (ToM) is a developmentally significant process. Initially, it seems that young children assume just one reality, which is that which self-evidently exists in their own minds. What is known is assumed to be known by all. The dawning realization that others possess minds of their own opens the awareness that those others also have ideas, though initially in a restricted sense and with an important limitation: the alternative ideas that have come to be accepted are not treated as equally possible alternatives, but as absolutes ("right" or "wrong"), depending on whether they conform to the one known and absolute version of what is. The absolutist (Kuhn 2005) view that "the way things are" is shared by everyone has implications for the development of argumentation skills, because the possibility that others might hold "false beliefs" does not reach the agenda. With increasing experience and corresponding with children's maturation to early adolescence, the appreciation of others' ideas progresses to a "relativist" quality, when alternative beliefs are more readily accepted as genuine options. This tolerance of ambiguity, emerging during adolescence, can be bewildering and may lead many young people, males especially, to seek refuge in the imagined "certainties" of science. Resolution arrives with the development of a value system that allows claims, beliefs, or arguments to be weighed against warrants and evidence, where alternatives are reflected upon by reference to a system of judgment in an "evaluativist" mode. So it is that "argumentation" has become integral to some science education programs, though there is evidence that the evaluative quality of reasoning is not easily achieved. The appreciation that situations may lack sufficient evidence to inform a decision is challenging, and the absolutist and relativist qualities of performance are by no means absent in many forms of behavior in adult life.

The Development of Inquiry Skills

Progression in the manner in which evidence to support claims is gathered has been relatively well researched by science educators. Systematic empirical inquiry is a defining feature of scientific behavior, which in many curricula is prioritized over other considerations (such as science subject matter). Scientific inquiries can be deconstructed into subsets of process skills that contribute to evidence-collecting and hypothesis-testing procedures in which learners gain increasing autonomy and control. These skills (usually encompassing hypothesizing, controlling variables, observing and measuring, collecting data, and interpreting or evaluating results) are called upon in planning and conducting investigations. Each skill is to some degree subject to its own developmental trajectory. For example, hypothesizing can be thought of as the expression of an idea in a form that may be tested empirically, so is dependent on the developments described above in the domain of ideas and evidence. Formally considered, an investigation should assume a null hypothesis, that is, that the outcome of any treatment or independent variable has no effect, but younger learners may seek to conduct an experiment that “proves” their idea.

Observation, quantification, measurement, and the defining of variables develop in a closely related manner. Accurate observation can be encouraged to develop, with stereotypes and theory-laden perception brought to metacognitive awareness and displaced by accurate recording. Children in their early years will be able to handle nominal (categorical) variables, defined by simple observable attributes such as color and shape, moving to ordinal variables defined by relative magnitude; gradually quantification is introduced, allowing interval variables to be handled. This increasing complexity will, in time, be applied to the coordination of both the dependent and independent variables.

Quantification tends to proceed from nonstandard (handspans, arm spans, footsteps, etc.) to standard metrics, starting with the familiar human scale of experience before moving to macroscopic and microscopic scales that require measuring devices. Over time, measurement reliability and precision increase, as well as the complexity of the units used. For example, distance and time are simpler for learners to handle than the relational concept of speed. The recording of outcomes may start with pictograms, moving to tables, bar charts, and line graphs. Causal relationships are observed and described in everyday events from an early age, so that with experience, learners begin to operate the distinction between the independent variable (the cause, such as angle of the sun in the sky) and the dependent variable (the effect, such as shadow length).

Younger children are encouraged to begin their inquiries using “fair testing,” where the teacher encourages consideration of the factors that might influence the outcome in an investigation. This level of development is often characterized by children’s desire to “control everything,” even down to consistency in the clothes they wear. Identification of valid control variables requires a greater understanding of the conceptual system under consideration than is likely to be available to younger children.

Progression in Conceptual Understanding

For science educators, the end of the twentieth and beginning of the twenty-first century was a time of enormous interest and research activity into learners’ conceptual understanding. Piaget’s structuralist epistemology was being increasingly questioned, though stage-developmental interpretations of progression continue to have significant support. By contrast, the Genevan nondirective clinical interview technique, together with classroom variations that have in common the resolve to heed carefully learners’ ideas, to take them seriously as indicators for intervention, is an enduring legacy. This tranche of inquiry shares a concern to understand the ideas pupils bring with them to their science lessons, prior to formal instruction. As a brief example, the evaporation of water from puddles and from washing on the line is an everyday phenomenon experienced by children prior to any formal instruction. Children will make their own sense of these events and we should make no assumptions of a unifying causal mechanism being understood to explain the shift from wet to dry. For children lacking any concept of object permanence, the water in the puddle may be believed to have “disappeared,” its shift to a state of nonexistence being unproblematic. In other contexts, it may be asserted that the water has “soaked in” or traveled to the source of the heat (the sun or a hot radiator) that caused it to move. (Look inside the hot radiator and you will find the missing water.) With experience, conversations, and exposure to secondary sources of information, the macroscopic appreciation of water as existing in three states will be grasped. With formal instruction, a microscopic model that makes sense of matter as particulate will be introduced, though with the salutary reminder for teachers that the model may be filtered or distorted by earlier understandings. With awareness of such possible conceptual milestones, teachers can apply not just science subject matter knowledge but pedagogical content knowledge (PCK) to their instructional strategies.

In the last 30 years, constructivist research has gripped science educators’ imagination for its relevance to daily classroom experience. One outcome is a bibliography of over 8,000 entries compiled at the IPN (Leibniz Institute for Science and Mathematics Education at the University of Kiel) that documents research on teaching and learning science from constructivist perspectives, theoretical and empirical, from leading journals and publications in English and German, covering the period from the late 1970s to 2009, by which time Internet search functionality was felt to have made continuation of the compilation redundant. The research, however, continues, and in a sense will always need to be updated, so long as the broader science endeavor continues with new insights and discoveries, while curricula adapt to changes in priorities and in understanding. The ambitious AAAS Project 2061 (AAAS 2007) is one example of an ongoing program (the start and end marked by the 75 year cycle of the Halley comet's visibility from the Earth) that intends to improve education for 4–19-year-olds by detailing such developmental links and trajectories in the growth of understanding.

The "nature or nurture" debate that preoccupied discussion of development during the first half of the twentieth century, together with questions as to whether intelligence should be construed as global in nature or comprising a range of "factors," has been the subject of a more nuanced form of research benefiting from the tools of neuroscience. Neuroconstructivists suggest multiple and interacting causation and epigenetic plasticity in the functioning of the brain. The digital impact on child development erodes the status of "pre-instruction," yet environmental influences such as social class must be acknowledged as background variables that have a significant impact on progress in learning of individuals and groups. Attempts to uncover, describe, or manage continuity and progression in science learning trajectories must be mindful of the turbulence attributable to such factors, which might help to explain the absence to date of conclusive contributions from the small number of longitudinal studies conducted. An apposite metaphor is that we are more likely to discern "migration routes" than very clearly defined corridors or trajectories. Nonetheless, the case for an evidence-based ordering of curriculum experiences that aim to support continuity and progression and which informs the formative assessment that supports effective teaching and learning is increasingly accepted as indispensible.

Cross-References

▶ Conceptual Change in Learning
▶ Constructivism
▶ Learning Progressions
▶ Piagetian Theory
▶ Socio-Cultural Perspectives on Learning Science

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Developmental Research

Kees Klaassen and Koos Kortland
Freudenthal Institute for Science and Mathematics Education, Utrecht University, Utrecht, The Netherlands

Introduction

Developmental research is a particular way of addressing the basic questions of why and how to teach what to whom. It involves a cyclical process of small-scale in-depth development and evaluation, at a content-specific level, of exemplary teaching-learning sequences. It aims to produce an empirically supported justification of the inner workings of such a sequence, which is claimed to be an important contribution to the expertise of teachers, curriculum developers, and educational researchers.

The Inner Workings of a Teaching-Learning Sequence

Two related elements are involved in the intended justification of a teaching-learning sequence about some topic. First, a detailed description of the desired (by the researcher) development in what students believe, intend to achieve, are pleased about, and so on, in relation to the topical contents. Second, a detailed explanation of why students' beliefs, intentions, emotions, etc., can be expected to develop as described, given such and such learning tasks and when guided by the teacher in this and that way. In this explanation the developmental researcher can rely on what may be called commonsense psychology, i.e., what everybody uses all the time to find out about and influence the mental life of others.

Developmental research tries to improve on the practical wisdom of experienced teachers, both in being more detailed and specific with respect to expectations beforehand and in being more systematic and impartial in evaluating whether or not the expectations have come true. Developmental research also aims at more than what can be achieved by a pretest-posttest research design. Such a design may give an indication *that* a teaching-learning sequence works or fails to work: are the intended learning goals reached, as measured by the progress from pretest to posttest? Developmental research also aims to understand in detail *how* and *why* the teaching-learning sequence works or fails to work: does the teaching-learning process itself proceed as hypothesized? It is precisely this detailed content-specific understanding of the process that promises to offer a worthwhile, evidence-based resource to guide professional practice.

Value-Laden Choices

Separate from the question why a teaching-learning process can be expected to proceed as desired, there is the question of why in the first place it is desirable that there is a teaching-learning process that proceeds in this particular way. Here values necessarily enter the picture. Since the outcomes of developmental research can only be properly communicated and discussed if placed within and judged from the value-laden context in which they are obtained, the developmental researcher will at least have to make explicit his value-laden choices. In particular the choices concern the goals he wants pupils to reach and the tenets or principles underlying the ways in which he wants to make pupils reach the goals (such as that students should be actively involved or that they should know all along what they are doing and why). The goals and principles together set the quality standard against which the developmental researcher himself wishes his outcomes to be measured.

From the value-laden character of learning goals and educational principles, it does not follow that they can be chosen freely. The learning goals cannot simply be decided on in advance. Whether they can be realized with sufficient quality, as measured by the developmental researcher's own principles, will have to be investigated. The connection between the educational principles and empirical investigation is much less stringent, and typically the developmental researcher tends to hang on to his principles. But if again and again he fails to meet the quality standard set by his principles, he may eventually begin to question the principles themselves or the theory from which they were derived.

The Heart of Developmental Research

Whereas commonsense psychology serves to explain why a teaching-learning process can be expected to proceed as desired, there is no theory that serves to actually design the teaching-learning process itself. The developmental researcher will benefit from a deep insight into science, its relations to technology and society, its philosophical foundations and its historical origins, and he may well be inspired by one or another psychological or learning theory. From all of this he may even have derived the goals and educational principles that set the quality standard which the teaching-learning activities he is to generate in the particular case at hand should meet. This standard may function as a checklist, make the developmental researcher receptive to useful ideas, and make him recognize a good idea as such. But the quality standard plays no further facilitating role in actually generating particular teaching-learning activities. The generation of a particular teaching-learning process is an activity sui generis and the very essence of developmental research. In the literature it is variously described as a process in which one's goals and educational principles are applied, implemented, translated, transposed, embodied, given content, or operationalized. But despite all these characterizations, it is a process that refuses to be regularized. Just like any creative process, it is a matter of finding local solutions to local problems. It depends on skill, sweat, talent, persistence, and a good deal of luck. Success or failure may critically depend on details such as the actual wording of tasks.

Vital Methodological Components

One vital methodological component of developmental research concerns the construction of a so-called *scenario* or *hypothetical teaching-learning trajectory*. This consists of the value-laden choices (see section "Value-Laden Choices" above) and the justification of the teaching-learning sequence (see section "The Inner Workings of a Teaching-Learning Sequence"). Simply making explicit the reasons for one's expectations about how the teaching-learning process will proceed may in itself already be sufficient to bring to light quite a lot of wishful thinking. Triangulation in the form of discussing one's scenario with colleagues will make the expectations more realistic by diminishing cases of tunnel vision.

A second vital methodological component is to put the design to the test. This involves the use of the scenario as a theoretical prediction of what will happen. The test then provides the evidence in light of which the scenario is to be evaluated. The comparison of the prediction to what actually happens is not straightforward. What actually happens will have to be interpreted in terms of what, at various stages of the process, students believe, mean by what they say, intend to achieve with what they do, and so on. Here too triangulation, in the sense of coordinating the interpretations of various researchers, is a good methodological advice, if only to avert the danger of seeing what one hopes to see (one's predictions). Proceeding in this way, and relying on commonsense psychology, the researcher can make his interpretation as rigorous, systematic, and objective as can be.

A third vital methodological component consists in reflection on the test, in order to improve the scenario in the face of all the points where the expectations did not come out. In some cases it may be possible to "explain away" a deviation. This may happen if the teacher did not guide the activity as intended, while there are indications that students would after all have done what they were expected to do if the activity had been guided as intended. More frequently the deviations reflect a clear need to make adjustments, though typically it will not be so clear which adjustments will suffice. Since a scenario is a highly interrelated complex, a failure that clearly emerges in one area may just be a symptom of a problem elsewhere. Another aspect of the interrelatedness is that necessary changes in one area are likely to require changes in several other areas. Some further, and deeper, complexity may arise if one decides not to make adjustments to the design in order to better realize the process that one wanted, but instead to make adjustments to what one wants the process to be like. That is, one may feel a need to adjust one's educational principles or learning goals.

Nature and Use of Outcomes

The aim of improving a scenario cannot be to eventually arrive at "the ultimate" scenario – one whose predictions will come out in exactly the predicted way. All that matters is that a scenario can be judged *good enough* to serve as a valuable guideline for understanding and guiding what goes on in actual classrooms. In each actual case the teaching-learning process will without doubt meander in a somewhat different way around the main predicted path. Several revisions are typically needed before one is even willing to consider the question whether or not a scenario can be judged good enough, and the first revisions are likely to require considerable adjustments. But no matter in how many classes or with how many teachers one has tried a scenario, the claim that it is good enough will always be of the following kind. If handled with proper care, the teaching-learning process will proceed more or less as intended, under normal circumstances. Despite the inherently vague nature of such claims, they are worthwhile, evidence-based contributions to the expertise of teachers, curriculum developers, and educational researchers.

The explicit specification of the value-laden choices and the detailed account of the envisioned teaching-learning process allow a teacher to get a feel of how the process appeals to him. In combination with the empirical support, the teacher can form a judgment as to whether or not he can see it work in his circumstances or see himself able to adapt it to his specific circumstances. In this sense a good enough scenario allows a teacher to reach an informed decision about whether or not to make an effort to use it.

Developmental research aims to engender progress in science education research in at least three ways. First, within the quality standard set by a given matrix of learning goals and educational principles, one good enough scenario may arguably better meet the standard than another one. Second, within the quality standard set by fixed educational principles, for a growing number and variety of topics (with associated learning goals), one may be able to produce good enough scenarios. Third, researchers operating with different quality standards can critically discuss the ways in which their respective theoretical perspectives have differently shaped the concrete activities in their respective teaching-learning sequences. At least this may lead to clarification of the educational principles or theoretical perspectives at stake and perhaps even to argumentation about which ones are better. Above all such an exchange will keep theoretical considerations firmly secured to what they are supposed to be relevant for: concrete teaching-learning activities. This is progress too, when compared to the abstract and freewheeling manner in which theoretical frameworks are frequently discussed in the literature.

The developmental researcher does not expect progress in the form of some general body of knowledge by virtue of which curriculum development will be made easier or more efficient. In this respect developmental research may differ from design-based research, in which design principles are often supposed to play such a facilitating or enabling role. It is rather by being exposed to a lot of scenarios, and to empirical tests and critical peer discussions of the scenarios, that curriculum developers are expected to benefit from developmental research.

Drawbacks and Boundaries

There are important educational issues that typically fall outside the scope of developmental research, such as the following: How can one make the value-laden choices of the developmental researcher a major concern of many teachers? What are useful techniques for teachers to make an envisioned teaching-learning process happen in their classrooms? What about large-scale implementation or dissemination?

Developmental research does not sit easy with the current emphasis on quantity of "output." It takes quite a lot of effort and time to produce a good enough scenario, and because of the formidable complexity of a scenario, it is hard to report concisely its justification and its test. This puts serious pressure on the progress that developmental research aims to engender in what it considers to be the core business of science education research: to construct, critically discuss, and empirically evaluate detailed content-specific justifications of teaching-learning sequences.

Cross-References

▶ Learning Progressions
▶ Model of Educational Reconstruction
▶ Teaching and Learning Sequences

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Dewey and the Learning of Science

David Wong[1] and Kevin Pugh[2]
[1]College of Education, Michigan State University, East Lansing, MI, USA
[2]School of Psychological Sciences, College of Education and Behavioral Sciences, University of Northern Colorado, Greeley, CO, USA

The connection between John Dewey and science education is enduring, vast, and varied. It would not be much of an exaggeration to say that Dewey had an influence on nearly all aspects of science education. Nevertheless, three influences stand out. First, Dewey proposed that the mind evolved in response to problem-solving situations and, consequently, the mind functions best in practical, problem-solving situations (e.g., Dewey 1916). According to this theory, learning is most effective when undertaking in the context of problem-solving and real-world situations. Second, similar to William James (1890), Dewey (e.g., 1938) firmly believed in the continuity of experience, where past, current, and future experiences were inextricably linked. This view foreshadowed modern constructivism including such principles are the importance of real-world experience and the role of prior knowledge in learning. Third, Dewey (1913) proposed that interest is a necessary component of learning. Interest activates a process of meaningful learning culminating in understanding instead of rote learning. Interest develops from connecting learning to prior experience, and it motivates the application of learning in everyday experience. These three ideas were foundational to the progressive era of education, which DeBoer (1991) identified as spanning 1917–1957. Within the field of science education, progressivism was characterized by dissatisfaction with educational practices that were too teacher centered and with content too far removed from real-world problems and students' prior experiences (DeBoer 1991). Progressive science education sought to contextualize learning in meaningful problems, involve students in experiential learning, and connect science to students' prior experience and interests. These progressivist goals have persisted in science education and are prominent in the twenty-first-century movements emphasizing such things as inquiry or problem-based learning and culturally relevant pedagogy.

Charting Dewey's Influence: Scholarship in Science Education Journals (1992–2012)

Dewey's influence continues to expand. One way of describing the nature and strength of the connection between science education and the work of John Dewey is to examine how his work has been cited in science education journals. We examined the past 20 years of four prominent science education research journals: the *Journal of Research in Science Teaching*, *Science & Education*, *Science Education*, and the *International Journal of Science Education*. We recorded all substantive connections to John Dewey making note of the author and date and, most importantly, assigned a keyword describing the substance of the connection to Dewey. The list below is ordered according to the number of articles making substantive connections to Dewey's work.

Inquiry

Contemporary work by science educators clearly suggests they view inquiry as a distinctive quality of Dewey's work. Indeed, the works of Dewey frequently read by educators – "How we Think" (1933), "Experience and Education" (1938), and "The Child and the Curriculum" (1902), for example – all highlight intelligent activity as a pragmatic process of encountering problems, testing hypotheses, actively engaging with the problem situation, and reflecting on consequences. Science educators focused on inquiry have cited Dewey's work in both philosophical examinations of the nature of inquiry and practical examinations of learning activities and teaching practices.

Pragmatism and Epistemology

Dewey's view of the nature of knowledge and the means by which something becomes knowledge is associated with the philosophical school of pragmatism. In brief, pragmatism holds that the value of a theory or belief lies primarily in its consequences, specifically the success and value of its practical application (Dewey 1929). Areas of science education influenced by Dewey's epistemology and pragmatism include the proper interpretation of Dewey's philosophical views, the nature of science, and the practical implications of teaching science.

Reform

Many of Dewey's works highlight how inquiry – knowing and doing inextricably connected – is central in the proper quest for greater certainty (Dewey 1929). In establishing his view of inquiry and knowledge, Dewey frequently criticized long standing dualisms – such as the separation of mind and body, theory and practice, and reason and experience, to name a few – as artificial and hindering the productive philosophical discourse. Science education reformers have resonated with Dewey's spirit of open-minded liberalism and progressivism, especially his willingness to dissolve categorical boundaries and bring together traditions that have long stood in opposition (Dewey 1902, 1938). Dewey's work has been cited in discussions about the proper role of science education, the importance of authentic inquiry activity, and the vital role of democratic, inclusive processes in science education.

Experiential and Hands-On Learning

Dewey's theory of experience, particularly as articulated in *Experience and Education* (1938) and *Democracy and Education* (1916), states that knowledge comes from experiences with the real world, prior experiences form the basis of new learning experiences, and new learning experiences have the purpose of transforming future experiences in the world. Further, educative experiences involve both an active trying out element (e.g., experimenting) and a passive undergoing element (i.e., experiencing the consequences and developing meaning from them). Science educators have drawn on this theory of experience to advocate the use of direct experience with real-world objects, events, and situations. They have also drawn on this theory to describe the nature of science learning experiences and consider the qualities that make for effective learning experiences (e.g., need for reflection and theory building to accompany hands-on activity).

Aesthetic and Transformative Experience

Dewey's theory of aesthetic experience as best expressed in *Art as Experience* (1934) articulates processes involved in undergoing aesthetic experiences and identifies a particularly meaningful and transformative type of experience, which Dewey termed "an" experience (Jackson 1998). Science educators have drawn on Dewey's theory to identify aesthetic characteristics (e.g., anticipation building toward consummation) and transformative qualities of science learning. Regarding the latter, particular emphasis has been placed on how science concepts (like art) can enrich and expand everyday experience by transforming perceptions of the world. This work also draws on Dewey's construct of an idea from *How We Think* (1933). Models of science instruction focused on fostering aesthetic and transformative experiences have been developed from Dewey's work.

Dewey and the Learning of Science, Table 1 References to Dewey in Science Education Journals[a]

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(*continued*)

Dewey and the Learning of Science, Table 1 (continued)

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(*continued*)

Dewey and the Learning of Science, Table 1 (continued)

Topic	Citation
Other	***Reflection***
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	Democratic society
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	Lemke, J. L. (2001). Articulating communities: Sociocultural perspectives on science education. *Journal of Research in Science Teaching*, *38*, 296-316
	Pedagogical Content Knowledge
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	Interest
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[a]We examined the past 20 years of four prominent science education research journals: the *Journal of Research in Science Teaching*, *Science & Education*, *Science Education*, and the *International Journal of Science Education*. We list only articles judged to make substantive connections to John Dewey's work

Aspects of Dewey's Work Not Prominent in Science Education Journals

In addition to identifying the more common connections science educators have made to Dewey's work in the past 20 years, our review of four major science education journals also reveals aspects of Dewey's work that, perhaps surprisingly, have not received much attention.

The Importance of Subject Matter

In 1902, Dewey wrote "*The Child and the Curriculum*" to address what he perceived to be serious misinterpretations of his earlier works. Dewey felt that educators had taken his recommendations for child-centered education too far and, as a result, educators had neglected the importance of both the subject matter and the teacher. Dewey disagreed that educators must choose between child-centered or curriculum-centered approaches and, instead, argued that such an either/or dichotomy was false and unproductive. Dewey offered an analogy of an explorer (child) using a map (subject-matter idea) to illustrate how intelligent, thoughtful learning required both an active learner and the disciplinary structure of a subject area. The role of the teacher was to facilitate the having of educative experiences by the inquiring student (explorer) with the subject-matter ideas created by disciplinary experts (map). This central role of curricular ideas as well as the teachers' vital role in mediating between the child and curriculum – "psychologizing the subject matter" – received considerable attention in the 1980 and 1990s, largely in connection to Shulman's (1986) construct of pedagogical content knowledge. However, substantial connections in this aspect of Dewey's work seem to be relatively rare in science education research in the past 20 years (Avraamidou and Zembal-Saul (2005) is an exception).

Learning as Social and Cultural

Another important legacy of Dewey's work is an understanding of learning as a social and cultural process. Along with George Mead, Dewey developed a theory of the social origin of mind. He described learning as a process of meaning making through social interaction. This aspect of Dewey's work shares an epistemological foundation with sociocultural perspectives on science education (Lemke 2001). In addition, many of Dewey's writings on pedagogy emphasize democratic forms of education (see, e.g., *Democracy and Education*). Dewey particularly emphasized pluralistic participation believing that schools should give a voice to all and provide a means for even the disadvantaged to shape society. This focus of Dewey's educational philosophy foreshadowed current science education perspectives falling under a critical theory umbrella (e.g., Calabrese Barton 2003). Thus, it is surprising that few references to these aspects of Dewey's work are found in prominent science education journals over the last 20 years (Table 1).

Cross-References

▶ Conceptual Change in Learning
▶ Constructivism
▶ Ecojustice Pedagogy
▶ Epistemic Goals
▶ Inquiry, as a Curriculum Strand
▶ Interests in Science
▶ Socio-Cultural Perspectives on Learning Science

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Dialogic Teaching and Learning

Orlando G. Aguiar Jr.
Federal University of Minas Gerais, Pampulha, Belo Horizonte, Brazil

Introduction

There is an increasing interest in studies of classroom discourse to inform and analyze the process of teaching and learning science. The reason for that is a theoretical assumption that there is an intrinsic relationship between language and thinking. According to the sociocultural approach inspired by Vygotsky, humans learn by the mediation of signs. According to Bakhtin, language is a system of signs that allows us to share a sense of the world with others, and this process is achieved by joint participation on particular social activities. Thus, language is not a simple way of communicating to others but a means to create and share a sense of the world, a powerful system that allows us to think together. Besides, learning science implies learning the languages of science, which codes a specific worldview, related to the social practices of science in society.

This explains the interest of science education researchers in contributing to the mastering of discursive practices, which allows teachers and students to seek a common knowledge based on scientific concepts. Instead of just claiming that language is a powerful mediational tool, this research agenda seeks to understand which kind of classroom discourse favors the progressive appropriation by the students of scientific concepts and the understanding of science as a cultural enterprise of producing and validating knowledge.

Dialogue is an important aspect of language itself. Based on the Bakhtin work, Wells (2007) suggests that dialogue is the most powerful mediational tool used by children and adults to negotiate meanings in activity. According to this perspective, dialogue is a two-way bridge of sign-based activity that makes it possible for a person to enter into the system of shared meanings in a society. Through dialogue, the child (or adult) can construct her "meaning potential" and thus convert in her own words the words of others, according to her feelings, intentions, and personal understanding of the social and material world. Another reason for the importance of dialogue in science education research agenda is that it allows addressing the problem of how the students' existing informal ideas interact with the new scientific knowledge introduced in the classrooms.

Researchers in education, including in science education, have identified a variety of patterns of classroom talk. The most prevalent pattern of science classroom interactions is a triadic "dialogue" in the form of "initiation-response-evaluation" (or I-R-E) or "initiation-response-feedback" (I-R-F) structures (Mortimer and Scott 2003). These patterns are commonly identified as authoritative (or non-dialogic) as they are centered in the teacher's initiative and power, and it is the teacher who controls the agenda and the contents of talk.

Despite of the effort of many curricular reforms and teaching guidelines, dialogic discourse is still unusual in science classrooms. Results from a range of countries show that even teachers involved with innovative teaching projects (inquiry-based, problem-based, project-based, argumentative teaching sequences, among others) and from a range of school levels (from primary to undergraduate courses) adopt mainly triadic interactions in whole-class discussions. These paradoxical results reinforce the need to review the notion of dialogic teaching (Scott et al. 2006; Littleton and Howe 2010).

Moreover, it is necessary to distinguish teaching science from learning science. The presence of dialogue in the learning practices of the students in a particular subject does not always match the way in which the subject was taught. After all, teaching practices create opportunities for learning but do not determine what and how the students will learn. Thus, to address the topic "dialogic teaching and learning," I start by discussing dialogue in science learning and then exam affordances and constraints of dialogue in science teaching.

Learning as Putting Science into Dialogue

I adopt here a sociocultural approach that conceives learning science as a result of enculturation process. According to this perspective, in school science classes, students are being introduced to the ideas and practices of science and are making these ideas and practices meaningful in a personal perspective.

Learning science is an intrinsically dialogic activity. Meaning making is an interpretative and, thus, a creative activity; faced with new science ideas, each student must create his/her own models to relate these new ideas and tools provided by the teachers to his previous ideas and ways of knowing. For that, she must put the scientific ideas into dialogue to other types of knowledge and, particularly and because of the informal ideas she brings to the class, with the epistemology of everyday life. The world of science being taught often differs deeply from the students' perceived natural world, constructed by direct experience in everyday life.

Following Bakhtin and his circle, dialogism is a feature of human understanding of the world. According to him, any utterance is a link in a chain of human communication. Every utterance is a response to previous ones and seeks an answer to them. It means that there is neither a first nor a final word about any issue. Based on a conception of discourse as language in use in social life, Bakhtin states that any understanding must involve an active response to the words of others.

In the actual life of speech, every concrete act of understanding is active: it assimilates the word to be understood into its own conceptual system filled with specific objects and emotional expressions and is indissolubly merged with the response, with a motivated agreement or disagreement. To some extent, primacy belongs to the response, as the activating principle: it creates the ground for understanding. Understanding and response are dialectically merged and mutually condition each other; one is impossible without the other (Bakhtin 1981, p. 282).

The Bakhtinian concept of responsivity is related to a dialogic stance; this is conceived as a relationship in which the interlocutors perceive themselves to stand with respect to their addresses. The concept of responsivity also helps to conceive dialogic teaching as a cohesive and temporal organization of the students' educational experience, in order to enhance progressive development of their understanding.

What Counts as Dialogue in the Science Classroom?

Below I present four different ways of conceiving of the ideas of dialogism in school science. The first meaning is very popular among teachers and sees dialogue as just teacher talk with the participation of students. However, this is not dialogic in the manner in which Bakhtin conceived it; dialogic relationships do not coincide with conversation replies. Educational research demonstrates that most "dialogues" in [science] classrooms are just recitation scripts in which the students try to complete the desirable answer from the teacher. However, in some cases the teacher does address different points of views and reviews arguments from both sides to compare and contrast perspectives.

A second perspective about dialogic teaching is based on the Bakhtinian distinction between two different forms of discourse, one more open to divergent ideas – what Bakhtin (1986) called "internally persuasive discourse" – and the other more closed, expressing a single perspective and demanding its full acceptance, namely, "authoritative discourse." Based on this distinction, Mortimer and Scott (2003) suggest that the basic feature of dialogic discourse in science classrooms is the consideration of students' points of view, besides the scientific perspective.

Dialogic discourse means, according to this approach, the encounter of different voices. Talk is considered to be more dialogic the more it represents the students' points of view, and the discussion includes both their and the teacher's ideas. This is in contrast with authoritative discourses where just one point of view, the school science perspective, is taken into account. According to the Mortimer and Scott, the consideration of different points of view in the science classrooms is fundamental for making connections between scientific and everyday ways of thinking and talking. The scientific perspective is considered as a social construction among others (religious, esthetical, philosophical, practical constructions), but a powerful one that has some specificity that must be acknowledged and experienced by the students.

The third approach to address the problem of dialogic teaching also comes from the philosophy of language of Mikhail Bakhtin. Contrary to the second approach (above), here dialogism is considered as a general notion of language, not as a particular kind of talk. Whatever kind of talk is being conducted in social life, every utterance is addressed to a listener and seeks to impact on that listener's understanding. One can say that, whatever kind of discourse is used in the classroom, dialogism will be always present, as the students use their counterwords to understand the scientific ideas introduced by the teacher. However, while this idea is very important, it is more closely related to leaning than to teaching; this third approach to dialogic teaching does not help to conceive which kind of discourse would provide best opportunities for learning.

The fourth approach to dialogic discourse emphasizes the distribution of power and control between teacher and students in conducting classroom discussions. From this perspective, attention is to be put on the interactive patterns of discourse, ranging from triadic moves (IRE or IRF) to open discussions. In IRE patterns, the student's participation is limited to giving brief responses to the teacher's questions, searching for the "right answer." However, triadic patterns are not always closed to students' views, as the third move from the teacher may involve not just evaluative statements but encouraging feedback, supporting students' participation (Wells 2007). Even then, the teacher is still in complete control of the discourse. This means that teacher's control may be not the main issue to be considered to address dialogic discourse in classroom settings. In some cases, whereas classroom interactions can be ideologically dialogic, in terms of considering multiple ideas and voices, it can be discursively non-dialogic, in terms of teacher control. So, it is important to note dialogic stances, which involve power and positioning from both students and teachers.

Considering such debate I reinforce the presence of multiple points of view as the main issue concerned with dialogic classroom discourse. However, such discourse may occur in a variety of forms, depending on:

1. Discourse participants (teacher and students or just the teacher)
2. Discourse initiative (power and control, more open or closed to students' initiative)
3. Symmetrical or asymmetrical orientations related to the types of knowledge being addressed
4. Level of interanimation of ideas (low level, when the students points of view are elicited but not further considered; high level, when the scientific perspective is constructed upon – or in opposition to – everyday reasoning)

To understand why dialogic discourse is so rare in educational practices and to develop ways to improve the quality of classroom talk, it is necessary to consider the culture and institution of schooling. Dialogue in the classroom setting must involve a real desire for mutual comprehension and the contrast of perspectives, but the teacher is in an institutional position that reinforces a resolution in the terms of the accepted scientific perspective. So, even in innovative classrooms, dialogic discourse is usually orchestrated by the teacher, who aims to control the flux of ideas in order to achieve, at the end, the scientific perspective as the best alternative.

In one sense, an ideal concept of dialogue in its radicalism has no room in school settings, as the participants of dialogue are not equally open to be convinced by the others. Besides, while there are multiple points of view being considered, they are not equipollent and equipotent in the manner Bakhtin identified in his analysis of the polyphonic novels of Dostoevsky. According to Bakhtin, two voices are considered equipollent and equipotent when they have equal force, power, and significance. In the novels of Dostoevsky, characters are considered from very different perspectives. The author did not take part in the debate; he has just presented the character's worldviews as poles of human understanding in social life. On the contrary, in school science teachers are always committed to the scientific perspective or, in other words, to the resolution of differences according to a certain position for the knowledge to be constructed. Thus, the institution of schooling constrains the ways in which dialogue can be conducted in the classrooms.

Dialogic Teaching Includes Both Dialogic and Authoritative Discourses

Teaching science involves two complementary dimensions that point in opposite directions but are not mutually exclusive. The first dimension relates to cultural heritage. Science, as a public knowledge, allows a picture of the world that often differs significantly from the perceived world of everyday life. Thus, science education demands guided interventions and supports so that the most important scientific ideas can be assessed and reviewed by the new generations. In this sense, teaching science involves a commitment to concepts, models, forms of reasoning, and language stabilized and agreed by scientific communities. Such forms of knowledge point to the past of science and ensure a collective memory for a given community. This is true both for the training of future members of communities of experts and also for ordinary citizens in contemporary societies.

The second dimension concerns personal understanding of science as a way to see and act on the world. Here science may be seen as a process of understanding the world, one that demands critical consideration of knowledge claims, argumentation based on evidences, and a sense of uncertainty faced to the phenomena to be explained. For this to occur, it is essential to design teaching situations in which students are asked to critically examine their views, as well as the scientific views that have been introduced.

Hence, to be implemented in schools, dialogic teaching involves both cultural transmission and meaning making of new ideas, by alternating both authoritative discourse and dialogic discourse. That is to say, scientifically productive classroom dialogue requires instruction that allows not just opportunities to discuss different ideas but also guidance to the new ways of thinking. According to Scott et al (2006), these two forms of discourse are not mutually exclusive, but complementary:

> The tension [between dialogic and authoritative discourse] develops as dialogic exploration of both everyday and scientific views requires resolution through authoritative guidance by the teacher. Conversely the tension develops as authoritative statements by the teacher demand dialogic exploration by students. So, both dialogicity and authoritativeness contain the seed of their opposite pole in the dimension, and in this way, we see the dimension as tensioned and dialectic, rather than as being an exclusive dichotomy (Scott et al. 2006, p. 623).

These two modes of discourse – dialogic and authoritative – accomplish different functions and can be engendered in different moments of a sequence of teaching. On one hand, authoritative discourse, focused on transmission of culturally accepted ways of thinking, allows cultural anchorage and a fidelity to scientific views. On the other hand, dialogic discourse provides opportunities for students both to make explicit their everyday ideas at the start of a teaching sequence and to apply and explore newly learned scientific ideas for themselves.

Ways of Promoting Dialogic Discourse in Science Classrooms

Due to the culture of schooling, dialogic teaching does not happen spontaneously. Therefore, it is important to consider teaching and discursive strategies designed to improve dialogism in science classrooms.

The stronger dialogic teaching design is related to inquiry-based teaching. According to Wells:

> When students pursue investigations, they develop ideas and acquire information that they want to share and debate; at the same time, the problems they encounter call for the joint consideration of alternative possible solutions. In these circumstances, students have reason to learn the skills necessary for engaging in productive dialogue and, over time, they also develop the disposition to approach problem solving of all kinds in this way (Wells 2007, p. 265).

Besides the importance of such approaches, even in countries and schools where educational reforms aim at promoting inquiry-based teaching, there is evidence that dialogic discourse is still rare in the science classrooms. One reason is that teaching materials do not offer necessary support for teachers to change the way language is used in classrooms and to know how to move from students' ideas to abstract scientific concepts.

There are research efforts to design teaching sequences in which the types of discourse around activities are in focus. The interplay between everyday and scientific knowledge involves planning turning points between dialogic and authoritative discourses. The study of such turning points – how and when they happen – is considered a crucial aspect to both understand and promote dialogic teaching.

Among the discursive strategies to improve dialogism in science teaching, there is a strong concern about the type of teacher's feedback. Many studies indicate the need for fewer evaluative statements from the teacher and more prompts and follow-up moves intended to encourage students to come up with new ideas, clarify their positions, and comment on other's points of view. The teacher's types of questioning are crucial to developing more dialogic whole-class discussions. Classroom studies also emphasize teacher's comments to the students' utterances, which allow the continuity of discourse and co-construction of knowledge. In some cases, this is done by "revoicing" the students' previous contributions, thus providing a collective memory to the class and encouraging further developments.

Dialogic discussions, in which students try out ideas and use language to think together, are more likely to occur in peer interactions and group work, free of teacher interventions. Besides, giving students time to prepare their thoughts about an issue or questions prior to a whole-class discussion greatly increases the diversity and quality of contributions. However, successful group work requires preparation, guidance, and supervision, that is to say, a balance between dialogic and authoritative discourse.

Preliminary dialogic discussions in the early stages of a new topic are commonly recommended by educational reforms and highlighted by many science classrooms studies. The purpose of such "exploratory talk" is to explore students' views about the topic and to connect these views to the scientific perspective to be introduced (Mortimer and Scott 2003).

Studies of science classroom discourse show that the move from authoritative to dialogic discussions at the end of teaching sequences, as advocated by Scott et al. (2006), is much less frequent than the use of dialogic discussions in the opening activities. Although teachers around the world are much more willing to explore students' views, the same is not true in respect to giving more space to students to discuss new contexts of use of the recently learned scientific ideas. Another reason is that the commitment of teachers to the scientific correct view is stronger than their belief in the need for responsibility to be transferred to the students in extending the scientific perspective to new contexts.

These activities may involve inquiry tasks in which the students are invited to work within the new scientific ideas. Another possibility is to promote the awareness of conceptual profile by comparing the results of pre- and post tests designed to address the differences between everyday and scientific perspectives on the topic.

Nowadays teachers around the world are facing a dilemma between promoting meaningful learning and being sensitive to the pressure for results in assessments. These assessments always reduce the dialogic space available in the classroom, as the pressure is to prepare students to give the right answer and not to discuss and justify points of view. Besides this, each new trend in the curriculum, instead of relieving this pressure, increases it with new demands on teaching.

Final Comments on the Issue

Based on this review, there is a clear need for more studies in dialogic talk at the end of a teaching sequence, when the students, working together, take the responsibility to use the scientific perspective to construct an explanation to new problems. It is also necessary to develop teaching sequences that use different strategies to link scientific and everyday points of view, highlighting the discursive strategies and communicative approaches to be used along the activities.

Sociocultural approaches in education mean to work in the tension between construction and instruction, discovery and transmission, freedom to explore, and guidelines to follow-up. Dialogic teaching may involve moves between these two types of discourses, dialogic and authoritative, to allow the active reconstruction of existing knowledge.

Today, the challenge is how to incline this balance to the dialogic side. There are many ways to do that: preparing teachers to do dialogic discourse in classrooms, designing teaching sequences in which the students should consider different alternatives to explain a phenomenon, providing links between phases and activities along a teaching sequence, preparing teachers to give feedbacks and prompts that guide the participation of students in dialogic discourse, and being conscious of the need to talk about ways of talking in classrooms. Besides that, there is a need to improve the effectiveness and impact of dialogic discourse in teaching sequences.

Instead of listing ideal features of dialogic discourse or dialogic space, we should understand that dialogue in school is both driven and bounded by predetermined curricular content and objectives. This is a clear constraint for those who think about dialogue as a completely open space for joint construction. However, scientific knowledge has no meaning for students and citizens if there is no interchange and communication between everyday and scientific domains.

Cross-References

▶ Acculturation
▶ Action and Science Learning
▶ Alternative Conceptions/Frameworks/Misconceptions
▶ Collaborative Learning in Science
▶ Discourse in Science Learning
▶ Inquiry, Learning Through
▶ Language and Learning Science
▶ Socio-Cultural Perspectives on Learning Science

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Didactic

▶ Didaktik

Didactic Transposition

► Transposition Didactique

Didactical Contract and the Teaching and Learning of Science

Guy Brousseau[1] and Virginia Warfield[2]
[1]LACES, Université de Bordeaux, Laboratoire Cultures Education Sociétés, Talence, France
[2]Department of Mathematics, University of Washington, Seattle, WA, USA

Introduction

The concept of *didactical contract* provides a powerful way of interpreting aspects of teaching, learning, and the interactions between teachers and learners. This concept has been developed over many years of experimental and theoretical research on didactical situations in mathematics. (Brousseau 1997).

For epistemological reasons, each "didactical contract" is to a large extent specific to the knowledge being taught. This specificity explains why the use of this concept has as yet expanded so little into other disciplines, although it has great potential in these.

In addition, the observation and explanation of various phenomena has led to the extension of the concept of didactical contract to the relationships of all the parties involved in education: parents, society, administration, academic societies, etc., always with respect to a specific (mathematical) concept.

Didactical contract has a great potential for enhancing our understanding of aspects of the teaching and learning of science. In the concluding section of the entry, some ways in which *didactical contract* has this potential are very briefly explored.

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Didactical Contract and Mathematics Education

Definitions

The teaching of mathematics is a social project of putting at the disposal of all the members of a society the means of participating in a common mathematical culture and benefitting from it. To each precise notion to be taught, the partners in teaching (i.e., the teacher, the learners, and the other parties mentioned above) associate expectations, obligations that each undertakes and benefits from, and the means by which they envisage (mutually or separately) satisfying these expectations and obligations as well as the consequences of not satisfying them.

A *didactical contract* is, in the broad sense, an interpretation of the set of these expectations and obligations, be they compatible, explicit, and agreed to or not. The study of the didactical contract in any classroom cannot be made solely by direct observation because a large part of these expectations and perceived obligations cannot be made explicit by the partners. Observation must therefore be complemented by modeling and experiments.

The Two Components of the Contract: Devolution to the Students and Institutionalization of Their Results

In mathematics education it is essential to know at every moment who, among the teacher, the students, and the wider *milieu* in which they are embedded, will take the responsibility for each mathematical statement that appears in class.

For example, during *autonomous activity* undertaken by students (such as the solving of a problem or more generally participation in a mathematical situation), the teacher refrains from any specific informative intervention.

This autonomous mathematical activity must be preceded by a phase of *devolution*, in the course of which the teacher provides information (e.g., a "direct" teaching [a lecture], exercises, assignments, etc.) that:

Allows him/her to move epistemological responsibility for what happens during the private or public development of the activity from teacher to student

Allows the students to then take on the responsibility offered to them during the mathematical activity

This mathematical activity of the students is followed by a phase of *institutionalization*, for the students and the teacher, consisting after an autonomous activity of:

Taking note of what has happened, of questions that have been resolved or are still open/unresolved, and of errors uncovered and removed in the course of the autonomous activity

Recognizing the new results obtained by the students if they conform to expectations and standard usage and the progress of routines that are in the course of being acquired

Classifying established pieces of knowledge that are well shared as references that may henceforth be used in class activities

Pointing out the questions that have not been resolved and the challenges to ponder

The nodal point of the didactical relationship is *devolution*. Devolution is the heart of the didactical contract, and is treated in a separate entry. The devolution of the right and capacity to express a personal mathematical thought is the essential act of teaching of this specialty. The study of it reshaped the foundations of the theory of didactical situations in this domain. But every discipline must address the devolution to the student of specific essential powers and rights; the prospects for and reality of devolution in the teaching and learning of any discipline undoubtedly merit studies similar to those already taking place in mathematics education.

Origin

The notion of didactical contract first emerged in 1980 in the course of a statistical and clinical investigation of some students having difficulties in mathematics but not other subjects (1975–1980). One of the cases observed gave a glimpse of certain causes of divergences and natural misunderstandings between the reciprocal expectations and possibilities of the teacher and student (Brousseau and Warfield 1998). Gaël, 8 years old and quite intelligent, responded to a problem involving looking for the unknown term in a sum in the manner of a 4-year-old. He happily refused to accept responsibility for the truth of what he said and thus did not enter into any solution procedure or, especially, a search procedure. This difficulty made starkly apparent the theoretical impossibility of forcing a child to take on a mathematical situation. The case was resolved by a sequence of situations – of "contracts" – to which he gave his agreement. But the theoretical problem remained and revealed profound flaws in the classical conceptions of the teaching of mathematics.

This concept of didactical contract then made it possible to explain observations such as the following (real example). Some teachers posed to their students absurd questions like the following: "On a boat there are 15 goats and 26 sheep. How old is the captain?" The students added up the numbers and said "41 years old!" Some commentators were outraged, claiming positions such as "Teachers are making students more stupid rather than more wise!" Further investigation revealed that the students thought the problem was absurd. When asked why then they answered it, they replied "Because the teacher asked [the problem]!" "And if the captain was 53 years old?" "The teacher didn't give us the right numbers!"

Put in simple terms, the notion of didactical contract provides a most plausible explanation for this student behavior: Past experience had led these students to the intuitive view that the quite implicit "contract" under which their mathematics classroom operated was that whenever the teacher asked a question, their responsibility was to answer the question and no more than this. They were certainly not to query the question, to suggest the question made no sense, or to suggest it was silly, and so on. A similar experiment with teachers in training gave the same results, with the same explanation being once more most plausible.

After its emergence in 1980, the concept of didactical contract was put to the test in the Centre de Recherches sur l'Enseignement Elémentaire des Mathématiques (the Center for Research on the Elementary Teaching of Mathematics – the COREM), which was conceived by G. Brousseau and created by the Institut de Recherche sur l'Enseignement des Mathématiques (Mathematical Education Research Institute – the IREM) of Bordeaux. The COREM functioned from 1973 to 1999 and comprised a scientific laboratory associated with a school with 14 classes of students aged 3-12, set up to permit scientific observation and the realization of long-term experiments on the teaching of mathematics in a controlled and limited context (Davis et al. 1986).

The didactical contract in the classroom depends tightly, but in a complex way, on the conceptions and requirements of various social and cultural institutions relative to each mathematical notion. The numerous phenomena that can only be explained by these interactions constitute the field of *macrodidactique*. This is discussed further in section "Macrodidactique."

Paradoxes of the Didactical Contract

Consider the usual classroom situation where the teacher wants to teach part of what she knows to a student who does not know it. There are a number of paradoxes inherent to this situation, paradoxes that in some contexts are in fact genuine contradictions.

(a) *Fundamental paradox*. The student cannot commit himself to a project about which he does not know the central issue, the precise objective, that is, the essential element of knowledge that is the focus of the project. Nonetheless, his engagement is indispensable – without it the teacher cannot achieve her goal. The teacher's engagement is as well, but she cannot commit herself about the certain success of a designated student. Every didactical contract is in effect a gamble – a necessary illusion.

(b) *Paradox of devolution*. The knowledge and will of the teacher must become the knowledge and will of the student, but what the student knows or does by the will of the teacher is not done or decided by his own judgment (a paradox similar to Husserl's of the master and the slave). The didactical contract finds its success only when it is broken: The student takes on responsibility for what he does or knows, independently of the teacher, and refuses her support.

(c) *Paradox of the said and unsaid* (a consequence of the preceding paradox). It is in what the teacher does not say that the student can find what he can say himself. The unsaid, the inexpressible, the uncertain, and sometimes even the false are the instruments of a living thought that establishes a truth and produces conviction about the reference knowledge.

(d) *Paradox of teleological learning*. A lecture turns the exposition of the conclusions of an historical creation, reorganized to follow deductive logic, into a prerequisite condition for student learning. Thus, the student is supposed to make use of what he will not know until the end of the process to organize first his comprehension and then his learning. He believes that in order to solve a problem, he must first "know" its solution.

(e) *The paradox of the general and the specific*. The teacher can only engage in procedures that are relatively general and common, for example, theorems, whereas the acquisition of a piece of knowledge is an individual and specific adventure of the knowledge in play in the problem.

(f) *Paradox of the actor*. Teaching is a production. The teacher needs to be a professional actor who must feign rediscovery with her students of knowledge that is highly familiar, even an old habit for her. The more she tries to be "natural" and spontaneous, the less credible and effective she will be (Brousseau and Otte 1991).

(g) *The paradox of uncertainty*. Knowledge is manifested and learned by the reduction of uncertainty that it brings to a given situation. Without uncertainty, or with too much uncertainty, there is no adaptation, and no real learning. The optimal development of individual or collective learning is thus accompanied by a normal optimal rate of errors. Global success is not a monotone function of the rate of instantaneous success. Arbitrarily augmenting or reducing it thus impedes and may delay both individual and collective learning (but the latter makes it possible to see to it that it is not always the same students who are doomed to provide the necessary errors.) The result is a new paradox: An increased rate of "instantaneous" success in the course of learning does not prove a better overall effectiveness.

(h) *The paradox of adaptation or lack thereof*. Excessive or premature adaptation to a piece of knowledge in conditions that are too specific can result in a particular piece of knowledge that may constitute an *epistemological obstacle* to the adaptation of this knowledge to new conditions (e.g., the practice of division in the natural numbers is associated to a meaning [sharing] that is an obstacle to its presentation in the decimal numbers when one needs to divide a number by a larger number [e.g., 0.3/0.8]).

(i) *The paradox of rhetoric and mathematics*. In order to construct the mathematical knowledge of students and its logical organization, the teacher uses various rhetorical means to capture their attention. The culture, pedagogical procedures, and even mathematical discourse abound in metaphors, analogies, metonyms, substitutions, figures of speech, etc., of nonmathematical means, against which mathematical concepts are often constructed.

(j) *The paradox of culture and science*. The teacher is thus supposed simultaneously, as a specialist, to cause the rejection of what science has disqualified and, as one who institutes students into a culture, to teach that culture with its historical meanderings.

Division of Responsibilities Between Requesters and Holders of Knowledge

The following types of contract do **not** cause the initiator to engage directly with the initiated, or vice versa:

Esoteric contract. The *client* (i.e., the learner) poses a question and is responsible for the question, its relevance, and the use of the response; the *expert* (i.e., the teacher) provides that response and guarantees its validity without saying how he established it.

Exoteric contract. The *scientist* produces the question and the answer, of which she gives the proof; she shares the responsibility for it with her community. The philistine takes on that of the relevance and use.

Initiatory contract. The *initiator* shows how he conceives of the knowledge. He comments on it, accompanying it with appropriate examples and their solution. He thus guarantees the validity and pertinence of the knowledge presented but takes no responsibility for what the person being initiated does with it.

Contract of instruction. The *instructor* proposes exercises and takes cognizance of the responses of the *learner*. She corrects them and gives the explanations that are asked of her. She makes no guarantees about the learning.

The types of contract where the teacher undertakes to achieve a certain success from the learner are as follows:

- The *strong didactical contract*. The teacher commits himself to initiating a specific protocol, known to make it possible to obtain with a certain frequency the behaviors agreed to be characteristic of some precise piece of knowledge. He thus relies on a custom, a culture, or a science recognized by the partners (parents, society, administration, academic societies, etc.), to achieve an average result agreed to by the partners. The fact that some of the students have succeeded in learning the agreed knowledge suffices to prove that it has been taught. An obligation of the mean has been satisfied.
- The *commercial contract*. If the scientific or cultural references are shared by the partners and only under that condition, teaching may be made the object of a *commercial contract* for collective or individual teaching. Nonetheless, the client would be mistaken to believe, like the Tyrant of Syracuse, that he could thus purchase a nonexistent royal road. It would be an even greater error to believe that random punishments of the students, of their teachers, or of the didacticians could produce improvements that depend in fact only on our shared knowledge. The height of absurdity is reached

when it is the client-students themselves who wish to exercise this type of empirical control over the processes that involve them.

Observation of the Spontaneous Responses of the Teachers and of Their Effects

The reactions of a teacher to an error or a failure of the students are combinations of a finite list of types, depending on:

- Certain criteria of the situation. Whether the error is recognized or not, explicit or not explicitly or implicitly, whether it is partial or global, and corrected or not (abandonment without explanation or, worse, without correction is not well accepted in classical contracts)
- The means used to reduce uncertainty. Identical repetition or metonymic or metaphorical repetition (reformulation, analogy, change of context), decomposition either of the problem (into intermediate questions) or the class (into level groups), analysis at the meta-level (logical, mathematical, heuristic or graphic reminders or comments), etc.

While these types of responses are implicitly fairly well accepted in the strong didactical contract, their properties are very rarely recognized. Sustained observation and theoretical analysis have convinced us that no combination of these types of response is in all cases either better or worse than all the others. None is decisive in all circumstances. Only analysis of the particular situation makes it possible to bring out the optimal choice case by case. Bernard Sarazy has demonstrated experimentally the importance of didactical flexibility: Varying the types of response is the best strategy (Sarrazy B 2002).

Thus, nonspecific pedagogical methods, principally based on the hypothesis of the universality of cognitive processes and hence of methods of learning and hence, a priori, of the existence of valid general methods of teaching, cannot provide optimal teaching. Thus, the use of "universal" responses, theories, and methods may simplify the acceptance by the population of a pedagogical or didactical contract and lower the cost of work and of training teachers, but it cannot under any circumstance be the best response to the expectations for teaching.

Macrodidactic

The above hypothesis led to the study of the influence of the epistemological, scientific, cultural, social, or economic foundations on the didactical contracts currently in operation in different societies. The issue is to explain the expectations, the offers, and the demands of different components of society with respect to this or that specific piece of knowledge and to compare these expectations, offers, and demands with the possibility of responding.

This new field of research has developed over the last decade under the name of "Macrodidactique." It has offered explanations for phenomena like the failure of the reforms of teaching based on mathematical structures in the course of the twentieth century (New Math), that of the teaching of "problem-solving methods," the effects of standardized testing, etc.

By bringing out the effects of the beliefs and inappropriate requirements of various partners in the didactical contracts, this research makes it possible to look into current practices in a more scientific and convincing way. For example, determining which knowledge to teach only on the basis of an explanatory text, without mentioning the actual practices that have produced the knowledge, has contributed to the creation of a didactical fiction which today is an insurmountable obstacle to progress in that domain.

Didactical Contract in Science Education

The word *contract* is most commonly used to indicate an agreement – usually a legal one but sometimes not – between two or more groups or individuals. That use is most certainly pertinent here, although, equally certainly, not "legal" in the usual way. The essence of this construct that there is a "didactical contract" developed over time and very often implicitly between teacher and students is an intriguing and very valuable frame for considering the behaviors and dynamics in any classroom of any subject. It raises a range of critical questions for considering classrooms, for example: What teaching and learning behaviors are expected of each group (teacher and students) in this classroom? Why are these expected? Do students or teacher know that these expectations exist? etc.

Perhaps more significant is that the evolution of the construct in mathematics education has consistently pointed to the impact on the contract of the nature of the content that is the focus of the classroom at a given time.

To what extent are these studies relevant for the teaching of other disciplines, most particularly science (and more generally for education)? Monitoring the meaning of concepts by their use in precise situations is normal in all disciplines and particularly so for mathematics and science. But the heart of the didactical situation is a situation specific to the knowledge in question. Apart from a few general principles and a few methods, each notion poses by definition a problem that is specific to itself.

The interaction between both the teaching and the learning of "X" and the epistemological and ontological nature of "X" has received very occasional attention in the science education literature, but as yet far too little. This is the case even within the branches of science. For example, consider the content of "introductory mechanics" and "introductory DC circuits." At one level one might argue that these are very similar content areas and can be taught with the same broad pedagogical approaches – both involve difficult relationships between concepts and have disarmingly simple formulae that often "hide" the conceptual difficulty in these relationships; both are rich in student alternative conceptions that have profound impact on subsequent learning. But there are profound differences in the nature of the knowledge in each area: In mechanics observations are almost always direct (i.e., we do not need instruments to enable the observation), and analogies and models are almost never used; in electricity, on the other hand, observations are always indirect (can only be made via instruments) and analogies and models are so central that even the language used to talk about the knowledge is totally dependent on analogies and models. To make the point further, consider then the differences they will need to be in the didactical contract between teacher and students in the very specific context of the physics laboratory for investigations of phenomena in mechanics and in electricity.

Cross-References

▶ Communities of Practice
▶ Conceptual Change in Learning
▶ Constructivism
▶ Dialogic Teaching and Learning
▶ Didactical Situation
▶ Dilemmas of Science Teaching
▶ Metacognition and Science Learning
▶ Metaphors for Learning
▶ Milieu
▶ Motivation and the Learning of Science

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Didactical Situation

Colette Laborde
Cabrilog and University Joseph Fourier, Grenoble, France

Keywords

adidactic; Equilibration; Mathematical concepts; Milieu

Imagine a teacher who knows that she/he must miss a class next week and wants to communicate the lesson plan to a replacement colleague. How might the teacher convey the critical features of the lesson so that the colleague can reproduce (1) the same learning outcomes for the students and (2) the same meanings for the knowledge acquired by the students? One of the aims of the theory of didactical situations (hereafter denoted TDS) is to identify the critical conditions for situations that can be presented to students and within which students will carry out activities that will enable them to construct specific meanings and understandings of a given concept.

Several dimensions are intertwined in a teaching situation focused on specific learning outcomes. These dimensions include cognitive, epistemological, cultural, and social concerns. Hence, several theoretical frameworks have contributed to the development of TDS. One such framework is Piaget's theory of "equilibration"; this theory served a pivotal role in the evolution of the idea of "adidactical" adaptation. In this conception, students construct knowledge by becoming directly engaged in solving a novel problem, refining their concepts and strategies in light of feedback from a (material and social) milieu (Brousseau 1997).

Conceiving of knowledge as resulting from a social construction over a long period of time led to the development of the theory of didactical situations, starting from the hypothesis that knowledge cannot be reconstructed in a spontaneous equilibration process. Instead, conditions and environments must be organized to present students with questions or problems that require a reorganization of their thinking. Here, "situation" refers to a collection of problem-solving tasks and environments designed to evoke a particular form of adaptation on the part of students, supporting them in the process of knowledge construction.

A Theory of Relationships Between Situations and Knowledge

Conditions for learning a scientific concept are specific to the content being learned. TDS was originally used to model learning situations in mathematics, but it can be viewed as a theory of the relationship between situations and knowledge so it can be extended to, or reinterpreted in, the sciences. The notions of economy and coherence are central in these relationships. Knowledge in physics, mechanics, or biology provides coherent and unified interpretations of families of phenomena that can be seen as different. As such, the knowledge groupings provide economy in explaining these phenomena. For example, describing two objects at rest as an event involving action facilitates provision of a unified account of the actions of one object on the actions of another object, irrespective of whether there is motion or not (Ruthven et al. 2009).

Identifying this type of economy or coherence for specific mathematical and scientific concepts, therefore, requires an epistemological analysis. This may include an analysis of the genesis and growth of the concepts in the histories of mathematics and the sciences, especially in order to determine the extent to which obstacles are intrinsic to these concepts. The notion of "epistemological obstacle," originating from Bachelard's theorization of the growth of knowledge in the physical sciences, was extended by Brousseau for theorizing the learning of mathematics: "obstacles. . . from which one neither can nor should escape, because of their formative role in the knowledge being sought" (Brousseau 1997, p. 87).

Adidactical Versus Didactical

The distinction between an "adidactical situation" and a "didactical situation" is key to understanding the distance between Piaget's cognitive equilibration theory and TDS. "Adidactical" does not mean that no teaching intentions underlie the situation; it refers to the perspective of the student. In an "adidactical" situation, the student experiences the problem not as a problem created by the teacher with didactical intentions but as if it were a genuine problem similar to problems that can arise in her/his life outside of school and that she/he must solve.

Although the situation is conceived with didactical intentions, the way the problem is posed and its environment lead the student not to consider the teacher's expectations but rather to take ownership of the problem. The solving processes may include some equilibration processes to overcome cognitive conflicts.

However, although an early assumption in the development of the TDS was that teaching sequences could be organized around adidactical situations alone, it turned out that, when observing their implementation in the classroom, the theory did not take into account "the [inescapable] intervention of the (mathematical [or scientific]) culture through the medium of the teacher" (Brousseau 1997, p. 110). It led to the incorporation of a further stage of "institutionalization" in which the knowledge that students developed from an adidactical situation undergoes a process of socialization and codification through teacher interventions. The asymmetry of the positions of the teacher and the students, with regard to mathematical and scientific knowledge, and the role of language in conceptualization, as laid out in Vygotsky's theory, are also sources of TDS.

As stated above, the guiding epistemological hypothesis in TDS is that a mathematical concept takes its meaning from problems to which it brings an optimal solution. This epistemological hypothesis could be extended to the sciences to the extent that scientific concepts take their meanings in relation to the variety of situations of their fields of applicability. The corresponding cognitive hypothesis within TDS is that learning results from students adapting their thinking in response to some new situation where their existing knowledge does not support an efficient solution strategy. The solution pathways that students find it necessary to devise serve as the sources of new knowledge. Epistemological and cognitive considerations are, of course, not independent: the aim is to identify the conditions for a planned process of learning through which students construct knowledge and use those features which the epistemological analysis has identified as constituting the concept to be acquired.

The teaching sequence is organized around a succession of adidactical situations based on problems. This forms a learning progression in which the question proposed to students at each new stage arises from problems encountered in deriving solutions at the previous stage or from the consequences or developments of these solutions. This succession does not depend only on the prior epistemological analysis, but also on concerns of the local organization and functioning of particular situations within the teaching sequence. Collective sessions, gathering the various solving processes of students under the guidance of the teacher, take place between adidactical situations.

An adidactical situation depends on the problem being one where students have a starting strategy available to them, but this strategy turns out to be unsatisfactory in some way. The ideal is that students, as a result of observing the inadequacy of the initial strategy, will be motivated to look for an alternative strategy and that this will lead them to devise a solution strategy that provides a basis for constructing the intended new knowledge.

Thus, it is of crucial importance that students should become aware of the inadequacy of their tentative solutions and that they should receive information from the situation that enables them to move forward in developing more powerful solutions. The notion of "milieu" has been developed within TDS to refer to that component of the situation that offers possibilities of interaction with students, providing means of gaining feedback to validate or invalidate their solution strategies. Particularly where younger students are concerned, the milieu is often designed to capitalize on a context with which students are already familiar. This familiarity guides the opening exchanges between the situation and the students. Changing the context for each particular situation in the teaching sequence is impractical as it would require students to spend time coming to terms with a new context on each occasion. Moreover, if the same context can be maintained, students' greater familiarity with it facilitates their further exchanges. Finding a suitable context capable of serving over several sessions is therefore a critical issue in the "staging" phase of a teaching process.

The milieu is not only a material milieu but it may develop and incorporate scientific texts, arguments in a classroom discussion, and the prior knowledge of students. This is particularly the case for introducing explanatory models in the experimental sciences. Students cannot themselves elaborate scientific models. The Leeds research group (Ruthven et al. 2009) presented lower secondary school students, learning the behavior of electrical circuits, with a contradiction between their expectations and what happened in the material milieu. The teacher proposed a simple series circuit with a power source at one end of the room and a bulb at the other end with very long wires connecting the circuit together. Many students expected a short delay between connecting the circuit and the bulb lighting. This is not what happened and it was very clear for students; however, students could not build an explanation by themselves. The teacher had to introduce an analogy to the class to explain the behavior of the circuit. Orange (2007) proposed to distinguish between three kinds of milieu for modeling learning situations in experimental sciences like biology: the external milieu, the internal milieu of the student, and the internal milieu of the classroom made of explanations and interpretations socially accepted and shared in the classroom.

In TDS, the social organization plays an important role in the functioning of the milieu. Adidactical situations that aim at fostering the learning of the formulation of mathematical objects and relations are based on exchanges between two students. Student A and Student B build a team and they must solve a problem in a constrained environment. Student B has access to information for solving the problem only through Student A who must convey useful information (verbally or in writing) in a form that is understandable to B. Whereas A and B are partners in a formulation situation, in adidactical situations that aim at the learning of proof, A and B are opponents: Student A needs to win against Student B by formulating arguments that student B can never invalidate.

Didactical Variables

In a task, there are identifiable variables with values that condition the efficiency of specific solving strategies and that make alternative strategies inefficient or tedious. For example, comparing the size of two collections of objects calls for totally different strategies depending on whether the two collections can or cannot be seen simultaneously. If the two collections can be seen together, a counting strategy is not necessary, whereas if it is only possible to have access to each collection separately, counting becomes unavoidable unless the collections have a small number of objects and can give rise to a mental image. Thus, at least two didactical variables can be identified in this comparison task: the size of the collections and the type of access to them. Another variable is the presence or absence of the possibility of manipulating the objects – since the counting process is greatly assisted by the possibility of separating already counted objects from those not yet taken into account. In the previous example about circuits, the length of the wires is a variable that makes visible the erroneous character of a sequential and causal idea about circuits. Such variables are called "didactical variables" because they act as key levers in precipitating and managing the development of the expected trajectory of learning. Identifying such variables starts from analysis of the knowledge available to students, in particular knowledge of the procedures available to them for dealing with the task. Observation of how situations play out with students in the classroom may reveal further variables not identified through prior analysis.

Use of TDS

During its development, the theory of didactical situations gave rise to the design of teaching sequences which, when examined in the classroom context, led to modifications and refinements of the theory. Warfield (2007) offers an introduction to the theory by giving examples of sequences of situations that allow the reader to better understand the use of the theory. For about 20 years now, the theory has also served as a tool for analyzing the design of teaching sequences and their implementation. A notion such as that of the didactical variable can be used independently of TDS to analyze tasks and gain some predictive ideas about the way students would deal with them. Ruthven et al. (2009) interpret TDS as an "intermediate" theory assisted by the "adidactical situation" and "didactical variable" tools. TDS is also used in conjunction with other theories such as the anthropological theory of didactics for analyzing the progress of teaching as a change of positions of students and teachers with regard to knowledge (Sensevy et al. 2005).

Cross-References

- ▶ Didactical Contract and the Teaching and Learning of Science
- ▶ Learning Progressions
- ▶ Longitudinal Studies in Science Education
- ▶ Milieu
- ▶ Scaffolding Learning
- ▶ Socio-Cultural Perspectives on Learning Science

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Didaktik

Reinders Duit
IPN-Leibniz Institut for Science and Mathematics Education, Kiel, Germany

The European Science Education Research Association (ESERA) states in its constitution: "*Wherever the English phrase* '*Science education*' *appears in this document*, *it has a meaning equivalent to* '*didactique des sciences*' *in French*, '*Didaktiken der Naturwissenschaften*' *in German*, '*Didáctica de las Ciencias*' *in Spanish*, *or the equivalent in other European languages*." At least in continental Europe, the term "Didaktik" is widely used – however with a number of significantly different meanings that do not only concern subtleties.

The German *Didaktik* tradition (i.e., the tradition that has developed in the German-speaking countries) has been very influential in continental European countries – however to differing extents. In ancient Greek, the word *Didaktik* denotes actions of showing and indicating. While this meaning seems to be quite close to that of the English word "didactical," *Didaktik* as discussed here stands for a multifaceted view of planning and performing instruction. It is based on the German concept of *Bildung* which refers to the formation of the learner as a whole person. It concerns the analytical process of transposing (or transforming) human knowledge (the cultural heritage) into knowledge for schooling that contributes to Bildung. Clearly, this transposition viewpoint is a key feature of thinking about science instruction in terms of Didaktik.

Many recent attempts to improve science teaching and learning have put their major emphasis on changing teaching methods and approaches. But the science content structure *for* instruction should also be given significant attention. This is a key figure of thought within the Didaktik tradition. The *Educational Reconstruction* approach explicitly draws on it. The analytical process of transposing human knowledge into knowledge for schooling is at the heart of this approach. It has become a key concept of German science education and seems to be widely accepted within European science education.

A project was carried out in the 1990s by the German Institute for Science Education (IPN) in Kiel to investigate the differences and commonalities between the European *Didaktik* tradition and the more pragmatic Anglo-Saxon *Curriculum* tradition. Westbury (2000) points out that Wolfgang Klafki (1995), one of the most distinguished scholars in the Didaktik tradition, argues that American curriculum theory and Didaktik are not far apart, as they are concerned with the same set of issues. Westbury points to key differences between the Didaktik and Curriculum viewpoints. He argues that the Curriculum viewpoint is embedded within a pragmatic philosophical position. Accordingly the focus is on *how* things are enabled, while the Didaktik tradition predominantly focuses on the *why*. Hence, he comes to the conclusion that despite the commonalities of the two positions, there are also "fundamental tensions because of their very different culturally embedded starting points" (p. 36).

There have, however, been important developments since Westbury presented his analysis. Globalization of science education research has resulted in close cooperation of science educators around the world. These processes initiated a fruitful international debate on the various science education positions, which have not resulted in a uniform view but more often in the enrichment of national (or regional) views. More recently, in the United States of America, for instance, there have been serious attempts to analyze and discuss critically the European Didaktik position. Duschl et al. (2011), for example, claim "*that didaktik research is a good source for identifying conjectural pathways of learning that can be examined as learning progressions*." This claim is of particular significance as research on learning progression has become a major strand of science education research in the USA.

In order to illustrate the German *Didaktik* perspective discussed above, two key approaches will be briefly presented. The first is Klafki's *Didaktische Analyse* (Educational Analysis) published in 1969. His ideas derive from the concept of Bildung and rest upon the principle of primacy of the aims and intentions of instruction. These frame the educational analysis, at the heart of which are the five questions in Table 1.

Didaktik, Table 1 Key questions of Klafki's (1969) Didaktische Analyse (English Translation: R. Duit)

(1)	What is the more general idea that is represented by the content of interest? What basic phenomena or basic principles and what general laws, criteria, methods, techniques, or attitudes may be addressed in an exemplary way by dealing with this content?
(2)	What is the significance of the referring content or the experiences, knowledge, abilities, and skills to be achieved by dealing with the content in students' actual intellectual life? What is the significance the content should have from a pedagogical point of view?
(3)	What is the significance of the content for students' future life?
(4)	What is the structure of the content if viewed from the pedagogical perspectives outlined in question 1?
(5)	What are particular cases, phenomena, situations, and experiments that allow making the structure of the referring content interesting, worth questioning, accessible, and understandable for students?

Another significant line of thought within the German *Didaktik* tradition is the fundamental interplay of all of the variables determining instruction (Fig. 1) proposed by Heimann et al. (1969). In this model, students' learning processes are of key interest. The aims and intentions of instruction are the starting point for the process of designing instruction. The *interaction* between intentions and the other variables shown in the top row of Fig. 1 is given particular attention. Students' intellectual and attitudinal preconditions, as well as sociocultural factors, significantly influence the interplay of these components. They enable four key questions to be raised that shape the process of instructional planning: Why – What – How – By What.

It seems that attempts to improve science teaching and learning usually put a strong

Didaktik, Fig. 1 On the fundamental interplay of instructional variables (English Translation: R. Duit)

Intentions (aims and objectives)	**Topic of instruction** (content)	**Methods** of instruction	**Media** used in instruction
Why	**What**	**How**	**By What**
Students' intellectual and attitudinal preconditions (e.g., pre-instructional conceptions, state of general thinking processes, interests and attitudes) **Students' socio-cultural preconditions** (e.g., norms of society, influence of society and life on the student)			

emphasis on improving the way science is taught. There is no doubt that this is essential. However, the Didaktik tradition points out that also the science content itself needs to be seen as "problematic." A content structure *for* instruction needs to be developed that addresses students' learning needs and capabilities as well as the aims of instruction.

Cross-References

- ▶ Bildung
- ▶ Curriculum
- ▶ Curriculum and Values
- ▶ Model of Educational Reconstruction
- ▶ Transposition Didactique

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Digital Resources for Science Education

Angela McFarlane
College of Teachers, London, UK

How you approach the subject of digital resources in science education depends greatly on how you approach science education. Most science educators try to strike a balance between coverage of domain content, the methods of science investigation to establish that body of knowledge, and the skills needed to understand the first and hopefully engage with the second at some level. Perhaps surprisingly, the epistemology of science – sometimes described as how scientists think – is not always addressed, although school science expectations do typically include a broad category concerning the nature of science. At the school level this is commonly reduced to a description of science as a cycle of observation, deduction and testing, though this represents only one form of scientific inquiry, modelled on Baconian principles, and excludes the range of other valid methods used to gather evidence and build knowledge in science. The issues of how we think about science and how we treat the nature of science within science education are dealt with elsewhere in this encyclopedia. However, it is important to hold in mind when reading this entry that how you employ any digital resource, including the learning context and task built around that use, is as significant as the nature of the resource itself.

The range of resources available can support and enrich a wide range of inquiry approaches, as well as more didactic approaches to science teaching. In any classroom there is likely to be a mix of these approaches, with the balance determined by a range of factors including the curriculum and assessment regimes in place and teacher preference. Rather than attempt a comprehensive list of actual sources, which would soon date, the table below summarizes the commonly used types of digital resource in terms of the activities in which they are typically applied and the main affordances they offer.

Activity	Resources	Affordances
Researching/ learning about a topic	Web sites, tutorial programs	Wide range of content available via the Web, structured and interactive presentation to give feedback on learning
Creating an argument	Argumentation environments	Supporting the development of an evidence-based rationale
Developing a model or concept map	Concept mapping tools, argumentation tools	Creating links and building a representation of relationships between concepts
Planning an investigation	Word processing	Writing and editing are tools to aid thinking and improve a plan
Inquiry projects	Scaffolded inquiry learning environments, e.g. Webquests	Carrying out an inquiry-based activity in a supported virtual environment
Investigate a model	Modelling environments	Building and/or experimenting with representations of complex systems
Taking measurements	Data logging and virtual experiments/ models	Ability to collect more data, run more iterations, and capture events too slow or fast for traditional school instruments
Making results tables	Data logging, spreadsheets	Ability to share data and use a class results not just one group

(*continued*)

Activity	Resources	Affordances
Drawing graphs	Data logging, spreadsheets, databases	Patterns to reveal relationship between variables generated in real time; data can be displayed in a range of ways to achieve most powerful
Doing calculations	Spreadsheets	Ability to work with larger data sets, automate calculation, and investigate relationships
Searching for patterns	Spreadsheets, databases, simulations, modelling programs	Rapid manipulation and larger data sets support an investigative approach to data
Asking "What if?" questions	Simulations, modelling programs	Experimentation can be carried out quickly and easily in simulations and models to prepare for, enhance, or enrich benchwork
Comparing own results with other people's	Social media sites, school learning environment	Larger data sets are more powerful; sharing gives an experience of the social nature of much modern science
Presenting information in a report	Word processing, presentation software	Teachers and students can produce high-quality reports and present these to the class. This process can support students to get feedback on their work and develop their understanding of what they present
Knowledge building	Wiki, knowledge forum, Web 2 tools, online discussion forums	Communicating with peers locally or at a distance, seeking new information and feedback for collaborative knowledge building
Voting or developing social norms	Audience response systems, tagging and voting environments	A particular case of collaborative knowledge building

Digital resources relevant to science learning range from raw, unprocessed data to framework programs which facilitate the management of data, even to the point of building complex simulations of the original systems and processes, and almost all combinations of the two. Whether seeking to present content to be memorized, simulations to support inquiry, or tools to support lab-based experimentation, there are digital resources that can enhance the whole activity or elements of it as shown in the table. Collaboration tools also facilitate the extension of learning beyond the individual, to collaborate with classmates – to compare results or build and test arguments – to connections with learners and experts in online knowledge building fora. Whether the approach is to teach science content or how to think scientifically, or hopefully a mixture of both, there are digital resources to help.

Among the myriad possibilities that digital resources open up for science education is the genuine possibility to join the ranks of scientists who seek out and build new knowledge, not simply to replicate what we already have a solid evidence base to support – important and rewarding though that may be. Perhaps most significant is the opportunity for students to understand the nature of scientific knowledge, that it is built through human endeavor, testable and verifiable, and that even school students can take a crack at it.

The advent of citizen science has seen the growth of Web sites that give students and teachers access to raw data from ongoing scientific research. Perhaps one of the most well known of these has been the Galaxy Zoo project where images captured from fantastically expensive and cutting edge telescopes have been offered to the global population to examine and report on. This is an example of crowd sourcing intelligence. No algorithm can yet match the deductive powers of the human brain to recognize the patterns of a galaxy in an image of a star system, and no science team has the capacity to look at all the images they are capable of capturing. And yet the skills needed to see these patterns can easily be learned – indeed a simple set of questions comparing the image you see to a set of reference diagrams is all you need. And so a situation arises where a school student, with or without the encouragement of a teacher, can become part of a globally significant scientific research project by examining raw data and commenting on it with the very real possibility that they will be the first to sight a new astronomical phenomenon.

Now let us consider how such a resource could be used in a classroom. First, a teacher might use a computer and projector to show a class the Galaxy Zoo Web site, look at a few images, and perhaps show a result of a new sighting made through this project. This could be done in a wide range of curriculum contexts: an example of an astronomical phenomenon in a science topic and an example of the use of the Web in a lesson on digital technology. Alternatively a student may come to school with a presentation she has made based on her experience of working on the site and joining the cohorts of those reporting on new images as part of her project on astronomy. The project may have been spontaneous and her report part of a "show and tell" exercise not even aimed at science. However, an opportunistic teacher might then suggest that all the class look at the site at home, in preparation for a discussion the following week and to contrast this approach to scientific inquiry with the "fair test" model of practical work they are familiar with. There are many options, corresponding to the equally wide range of inquiry approaches and pedagogical designs that may be adopted by science teachers. The resources, however, remain neutral and accessible to many approaches.

Stepping back one stage further from access to raw data or processed digital resources, it is possible for teachers to access scientific instruments so that their students may actually collect data. Although it is unlikely that this will lead to genuinely new discoveries, there is still that possibility, and it certainly gives an authentic sense of the look and feel of working science. The Open Laboratory Web site, launched by the Open University in the UK, in 2013, is one example of access to a range of instruments and simulations of those instruments which students can operate through a computer screen. The site also underscores the notions that many twenty-first-century scientists don’t actually work with beakers and test tubes but sit at a computer screen that interfaces with instruments or with massive data sets and complex models built from them and that science is a collaborative activity with many individuals contributing to any breakthrough.

Again, such a resource could be used in many ways with varying levels of control by the teacher or learner, with a learner experience ranging from well defined to open ended. The site could be used to expound certain established areas of content, to explore and discover together or alone, and to experience science as a process or a body of knowledge or any or all of these in combination.

Given that the way the resource is deployed is as important as the nature of the resource in terms of the opportunities it might afford for learning, what then does access to digital resources offer to teachers and learners that transcends the affordances of traditional texts and real-world experiences in the lab or the field? Digital resources offer scale, mutability, and the opportunity to share, revise, and store. Instead of looking at a static data set (e.g., in a table form) or image, it is possible to access many examples, dynamically, comparing and contrasting, looking for patterns, and even gaining an understanding of the variation. For example, when teaching the topic of sound, it can be difficult to make a link between the frequency of a note and its representation on a musical scale. This is not a common approach in textbooks, yet a Web search will quickly unearth a range of descriptions of this relationship that help to build a link across the subjects of physics and music. It will include simulations and animations that help to bring descriptions to life. Once these various sources have been gathered, it is possible to capture elements, add a personal explanation, and make a presentation that explains the phenomenon to yourself (using appropriate citation!) and then to share this with a fellow learner or teacher. Feedback and comments from peers or teacher can then help the student to refine the accuracy and clarity of the end product. Finally, the end result could be shared or simply stored for later review and revision, either for a test or to integrate into further understandings or inquiries into the topic – perhaps in a music class or in a later science course. This example is theoretically possible without digital resources, but in practice could not be achieved easily, or to any level of scale. The essence of digital resources is that they make it realistic to teach and learn in ways that support genuine personal knowledge building rather than rote learning.

There are a few caveats to the use of digital resources in science education. Perhaps most important is that there is a great risk of replacing hands-on, sensory experience with digital alternatives. Just as playing a snowboarding simulation game will never result in one’s learning how to snowboard, nor will it ever replace the experience of actually swishing down a mountain, manipulating simulations will never entirely replace scientific lab or fieldwork. Used well, however, such experiences can extend and enhance the student’s inquiry into scientific topics. Also, there is a vital element of feedback entailed when a student works to create personal digital records: such products of inquiry must be personal, not simply cut and pasted with little thought, editing, or original commentary. Finally, there remains a gap between the theoretically possible and the achievable when it comes to supplying access to digital resources for students. Having a class of 30 access high-definition video on personal devices over a wireless network is likely to be problematic. So, careful planning and judicious use of resources both in and out of the school environment are required if any of the above scenarios are to be achieved through meaningful hands-on experience for all students rather than teacher demonstration.

Cross-References

▶ Argumentation Environments
▶ Blogs for Learning
▶ Concept Mapping
▶ Modeling Environments
▶ Models
▶ Simulation Environments
▶ Wikis

Dilemmas of Science Teaching

John Wallace
OISE, University of Toronto, Toronto,
ON, Canada

Keywords

Classroom management; Teaching dilemmas

The term *dilemma* is derived from the Greek (via Latin) terms di meaning two and lemma meaning assumption or proposition. A dilemma is a situation that requires a choice between two options that are, or seem, equally unfavorable or mutually exclusive, hence, the expression, "caught on the horns of a dilemma" – when opting for one choice over another, one is stuck uncomfortably on the horn of that choice and unable to do anything about the alternative option.

In educational contexts, the dilemma idea was explored in Berlak and Berlak's (1981) book *Dilemmas of Schooling*. Here, the authors examine how numerous curriculum and societal dilemmas impact on schooling. These include child as person vs. child as client, content vs. process, knowledge as given vs. problematical knowledge, learning as social vs. learning as individual, common culture vs. subgroup consciousness, equal vs. differential distribution of resources, and equal vs. ad hoc justice. The authors contend that the dilemma language can assist teachers to be critically aware of the consequences of these opposing dispositions and to develop patterns of resolution. They discuss an example of the control dilemma (whole class vs. individual) where a teacher is dealing with inattentive boys during reading time. She intervenes more frequently with the boys than she does with the girls, perhaps indicating an assumption that boys need more control than girls. The authors suggest that this dilemma could be resolved by employing any number of alternative teaching strategies, including differentiated reading materials for boys and girls, or giving both boys and girls more responsibility for choosing their reading matter.

Another take on dilemmas in teaching was presented by Lampert (1985), who paints a picture of the teacher as a dilemma manager. In one of her cases, Lampert describes a grade 4 lesson on the water cycle. One of the students in the case declares that water comes from the ocean, whereas the textbook answer indicates that water comes from clouds. In moderating a class discussion about which is the correct answer, the teacher avoids the dilemma trap by accepting that both answers are correct. In her analysis of this and other cases, Lampert rejects the notion of teacher as a "technical-production manager who has the responsibility for monitoring the efficiency with which learning is being accomplished" (p. 191, original emphasis). Rather, she sees the teacher as a dilemma manager, "an active negotiator, a broker of sorts, balancing a variety of interests that need to be satisfied in classrooms" (p. 190).

In their 2002 edited book, *Dilemmas of Science Teaching*, Wallace and Louden present a series of science teaching dilemmas through teacher-written cases. Accompanying each case is a set of commentaries by distinguished science education scholars and a synthesis by the editors. The cases present a range of dilemmas faced by science teachers, about science itself, about difference, about representation, and about teaching and learning. Three examples from the book illustrate the way in which dilemmas are played out in the science classroom.

The first case, entitled *To tell or not to tell*, involves the dilemma faced by a teacher who wants to encourage students to explore their naïve understandings of science (in this case electrical flow). At the same time, he finds that their understandings fall short of a robust scientific explanation of the phenomenon. According to Wallace and Louden, at the heart of this dilemma is the issue of who has responsibility for learning. "In order to move beyond a reliance on the teacher for the right answer, there is a need for students to accept some responsibility for learning.... Good teachers tread "the 'middle ground' on this issue mediating between the two extremes of telling (and therefore taking on some of the responsibility) and not telling (and encouraging students to take more responsibility)" (p. 203).

The second case involves the use of analogies in science teaching. The teacher in the case described the difficulties she encountered when she used the analogy of a city to explain the structure and functioning of a cell. The teacher found that because students had different understandings and experiences of a city, the analogy was useful to some and unhelpful to others. Moreover, the phenomenon (the cell) comes in different shapes and sizes. The dilemma for the teacher was how far should she push the city analogy before it becomes self-defeating. As the authors point out, managing this dilemma involves a two-pronged strategy of probing into students' experiences to increase their understanding of the analog *and* helping students understand how analogies are used in science to explain complex and variable phenomena.

In the third case, the authors examine the different responses of girls and boys in activities designed to explore series and parallel circuits. The boys quickly helped themselves to the equipment and adventurously experimented with different arrangements of batteries, wires, and bulbs. The girls were more cautious and soon found themselves falling behind, requiring direct help from the teacher. As Wallace and Louden put it, "The subject matter, the opportunities to compete for resources, the teacher's different responses to the boys vs. the girls all point towards 'boy-' rather than 'girl-friendly' science" (p. 84). The teacher is caught in the middle of this dilemma, whether to focus the lesson more on girls' experiences or boys. Managing this dilemma means attention to both realities, to enable girls as well as boys the opportunity to expand and explore their different experiences and understandings.

To summarize, science teaching is an activity rich with dilemmas. Teachers are required to balance many competing educational demands, for example, between attending to the individual and the rest of the class, between respecting students' naïve understandings and promoting canonical knowledge, between listening and telling them the answer, and so on. The best science teachers are those who manage their way through these apparently irreconcilable differences with diligence, good humor, and respect for all those involved in the teaching and learning process.

Cross-References

▶ Classroom Organization
▶ Pedagogical Knowledge

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Discourse in Science Learning

Gregory J. Kelly
College of Education, Pennsylvania State University, University Park, PA, USA

Keywords

Conversational analysis; Ethnography of communication; Sociolinguistics

Discourse practices and science learning

Discourse is the use of language in context. In each instance of use, discourse is constructed among people in some context, with some history, projections of future actions, and ideological commitments. As discourse entails more than the ideational communication, the broader contexts of social groups, cultural practices, and interpersonal goals need to be taken into consideration when deciphering meaning in interactional contexts. Social norms, expectations, and practices are constructed through discourse processes and, in turn, shape ways that discourse is evoked in each instance, thus instantiating the symbiotic relationship of discourse and sociocultural practices.

Discourse is central to the ways communities collectively construct norms and expectations, define common knowledge for the group, build affiliation, frame knowledge made available, provide access to disciplinary knowledge, and invite or limit participation. Such communicative processes are central to education. The ways that teachers and students use discourse in educational events have bearing on how learning opportunities are supported or constrained. In science classrooms the ways that teacher talk science, frame communicative norms, and engage students in the range of semiotics of the relevant discipline construct the nature of the scientific knowledge and practices available to be learned (Kelly 2007). Studies of student learning suggest that features of scientific discourse are not mastered as received knowledge through didactic instruction, but rather through participation as a member of a group in a discourse community. Students learn meanings of scientific terms through engagement in discourse and practices.

Scientific discourse includes some unique features, derived from the highly specialized nature of the epistemic communities constructing these discourse processes and practices. In professional and educational settings, scientific discourse is characterized by multiple modes of semiotic communication, including spoken, written, representational, inscriptional, and symbolic, among others. The range of semiotic communicative forms shows wide variation and is often alien to science students' ways communicating in others aspects of their lives. This may pose challenges to learners of science, as the unique linguistic forms of science including the use of passive voice and conditionals, technical vocabulary, interlocking taxonomies, abstraction and nominalization, and complex symbols and notational systems (Halliday and Martin 1993). Studies of classroom discourse have documented ways that it is common for science to be constructed through talk and action in ways often alienating to students, leaving the impression that science is difficult, reserved for cognitive elites, and regimented (Lemke 1990).

A central concern for science educators has been student access to scientific knowledge. Discourse studies have contributed by identifying differences between scientific discourse and students' everyday ways of speaking, knowing, and being in other settings. This concern for equity in science learning has led to studies of the ways that scientific concepts are constructed. In particular, the importance of uses of metaphors and analogies has been identified as a key component to the development of student understanding. Furthermore, there is evidence the variation of students' home discourse with that of science is an important impediment to learning. Students from language backgrounds, often falling along class, race, and ethnic lines, that differ from that spoken by scientist and science teachers face more serious learning challenges than students whose discourse background matches that of science teachers. Taking on a scientific discourse includes building an identity with the discipline and members of the local discourse community, which can be alienating for some students. Thus, studies of educational equity need to account for language variation, specific forms of scientific discourse that pose problems for learners, and ways that affiliation and identity are constructed through language use.

The study of discourse has also been viewed as important for student engagement, including inquiry approaches and student-led group work in laboratory settings. Inquiry teaching often involves students in scientific practices using language such as posing questions, providing explanations, communicating results, evaluating inferences, and critiquing ideas. As these practices are heavily language dependent, discourse analysis provides a way to consider how opportunities for learning are constructed in education events and how the merits of educational practice can be accessed. Inquiry instruction often includes students working with material objects to derive conclusions based on evidence. The processes of discovering how to make inferences, draw conclusions, and communicate results are interactionally accomplished through discourse. Thus, student reasoning can be viewed as a social process, highly dependent on the types of discourse moves available in their sociolinguistic repertoire.

One central practice emerging as relevant to many pedagogical approaches is argumentation. Argumentation refers to the uses of evidence to persuade an audience of the merits of a position. This is particularly relevant to inquiry approaches that place emphasis on evidence and explanation. Building an argument entails understanding the genre conventions for ways of aligning data, warrants, and claims. Furthermore, argumentation is often employed in interactive settings where students are able to make support and defend claims against criticism and counterclaims. Discourse includes the uses of signs and symbols, important for communicating and critiquing scientific models, graphs, and other knowledge representations. Argumentation is thus a learned discourse practice, with particular genre conventions that come to determine what counts as relevant data, a valid argument, sufficient evidence, and so forth.

Learning to teach and learning from teaching involve understanding how to employ, decipher, interpret, and produce discourse in the moment-to-moment interactions of educational events. Teacher education has become increasingly focused on the ways that science teachers learn to reflect on their practice and in particular how to use discourse moves to engage students in reasoning about ideas. As science education reform has increasingly focused on ways to help students understand concepts, models, and epistemic practices, teachers face the challenges of helping students engage with the subject matter in these ways.

Across the range of substantive topics of research and in various educational settings, a number of communicative issues have been observed. Often discussion in science classrooms is directed by teacher talk, following closely science textbooks. Such talk in the interactional context of whole-class discussion falls into a pattern of teacher initiation, student response, and teacher evaluation (IRE). This pattern of talk has implications for what is made available to learn, how the particular science discipline is positioned, and how students develop their identity with science. Yet, educational reformers have argued for a more expansive range of interactional contexts that include opportunities for an active role of students in classroom conversations. Mortimer and Scott (2003) propose a model to examine five important dimensions of classroom discourse: teaching purpose, science content, communicative approach, patterns of discourse, and teacher interventions. This model helps understand the nature of discourse events and provides a basis for designing teacher education with a focus on the centrality of discourse for science learning.

Discourse analysis refers to the study of language in use. To examine the range and types of communicative situations of discourse in science education, analysts have sought to understand how uses of discourse are situated in social practice and over time. Social practices, norms for interacting, and expectations about communicative demands are tied to the ways that language is used. Discourse analysis thus often considers how talk and action is shaped by the norms and expectations of the communicative events. This suggests the need for ethnographic and other research approaches that seek to understand broader cultural patterns of activity governing the uses of discourse. Such studies consider the micro-moments of interaction, the meso-level construction of practices through multiple interactions, and the macro-level analysis of cultural practices. Spoken communication occurs through both verbal and nonverbal channels. To understand meaning in interactional contexts, discourse analysis needs to consider pitch, stress, intonation, pause structures, physical orientation, proxemic distance, and eye gaze, among other paralinguistic features of talk.

The conceptual and epistemic goals of science education entail developing the linguistic repertoire of students. The perspective of discourse analysts suggests that learning concepts means being able to communicate with members of a group in an effective manner. As students come to learn science concepts and engage in scientific practices, they develop more expansive ways of speaking, listening, and interpreting the discourse of science and can be viewed as communicatively competent with members of a relevant community (e.g., other science students, scientists in a particular discipline, member of a community activist group focused on environmental issues). Thus, effective uses of discourse enhances student learning by expanding the range of their repertoire to communicate and learn from others. Such a view is consistent with sociohistorical learning theories that consider cultural tools, signs, and symbols that mediate social interaction as a basis for learning (Vygotsky 1978).

The implications for science teaching of discourse studies in science education are clear. As engaging with science includes working in a range of semiotic fields, teachers need to find ways that students are given opportunities to use words, signs, and symbols to communicate and interpret meaning in a variety of interactional contexts and settings. By providing opportunities for students to learn through speaking, listening, and using concepts in context of use, i.e., while engaging in scientific practices such as observing, reasoning, explaining, or providing evidence in an argument, teachers can engage students in science through active participation where learning is most likely to occur.

Cross-References

- ▶ Activity Theory and Science Learning
- ▶ Argumentation
- ▶ Discussion and Science Learning
- ▶ Socio-Cultural Perspectives and Characteristics
- ▶ Sociology of Science

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Discovery Learning

David Hammer[1] and Richard Gunstone[2]
[1]Department of Education, Tufts University, Medford, MA, USA
[2]Faculty of Education, Monash University, Clayton, VIC, Australia

"Discovery learning" is a label that has been prominent in discussions about education, including science education, since at least the 1940s.

Like all popular terms in education, discovery learning has taken on a range of meanings, but most often it refers to a form of curriculum in which students are exposed to particular questions and experiences in such a way that they "discover" for themselves the intended concepts. The student's inquiry is usually "guided" by the teacher and the materials, for example, through "Socratic" questions, because no one expects them to arrive on their own at ideas it took scientists centuries to develop.

Many scholars, including the authors of this entry and the editors of this encyclopedia, see the term as having little value today. This is in part because some proponents of "discovery learning" make extreme claims for the benefits they see in student discovery of concepts and in part because the term has become rather debased by its highly inconsistent use in a range of educational debates (including as a pejorative term) (Hammer 1997).

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Discovery Science

Robert Mayes[1] and Bryan Shader[2]
[1]College of Education, Georgia Southern University, Statesboro, GA, USA
[2]Department of Mathematics, University of Wyoming, Laramie, WY, USA

Keywords

Computational science; Data-intensive science; Information literacy; Scientific computing

Technological advances over the last several decades have disrupted the very nature of our day-to-day lives, as well as scientific research. Grand challenges facing society drive research and education to address questions that require intensive computation and data analysis. Such grand challenges include:

- What is the impact of global and regional climate changes?
- Can carbon dioxide be safely sequestered to minimize the release of greenhouse gases?
- How can we better predict and plan for natural disasters (earthquakes, tsunamis, wildfires, avalanches)?
- How can breakthroughs in genetics be used to cure/fight cancer and other diseases?
- What is the structure of the Milky Way galaxy?

As a result new paradigms of science have emerged. The **empirical method**, the application of experimental data to predict and describe natural phenomena, arrived on the scene 3,000–4,000 years ago and was evident in the lists of Pythagorean triples in Babylonia; in an Egyptian medical textbook (circa 1600 BC) that applies examination, diagnosis, treatment, and prognosis to the treatment of disease; and in charts of planetary motion. The Age of Reason (1400–1700 AD) brought the birth of **theory**: science based on principles that are developed through the use of models and generalizations. Theory was manifest in Galileo's studies of motion; the writings of Hailey, Kepler, Pascal, and Huygens on planetary motion; the development of calculus to explain mechanics by Newton and Leibniz; and Napier's formulization of logarithms. (See *The Fourth Paradigm*: *Data Intensive Scientific Discovery* (Heyet al. 2009) for a detailed discussion of this history.) Until recently, the empirical method and theory were considered the two legs of science. Over the last 20 years, with the advent of powerful computing capabilities, two new science paradigms have arisen: computational science (scientific computing) and data-intensive science (data-centric science).

Computational Science or Scientific Computing

Scientific computing has emerged as the third leg of science, joining theory and experiment. It allows us to attack previously unsolvable problems and make transformational advances in science and engineering to address global challenges in energy, environment, and national security (Wadsworth 2006).

Scientific computing is not computer science per se. Computer science develops technological hardware and software and is a discipline unto itself. Scientific computing is the use of the hardware and software to guide the discovery of new science. Scientific computing is embedded in mathematics, science, and the humanities; it complements experiment and theory, but does not replace them. As others have put it:

> It is both the microscope and telescope of modern science. It enables scientists to model molecules in exquisite detail to learn the secrets of chemical reactions, to look into the future to forecast the weather, and to look back to a distant time at a young universe. (Fosdick et al. 1996)
>
> Scientific computing focuses on simulations and modeling to provide both qualitative and quantitative insights into complex systems and phenomena that would be too expensive, dangerous, or even impossible to study by direct experimentation or theoretical methods. (Turner et al. 2011)

Examples of the use of scientific computing include the study of wind turbines, oil and gas recovery, CO_2 sequestration, seismology, hydrogeology, cloud formation, carbon and water cycles, wildfires, and genetic adaptation.

Data-Intensive Science

The explosive use of personal data, new data collection technologies, and the capabilities and speeds of modern personal and supercomputers has resulted in a wealth of information and data. Simulations of complex models are generated on a 24/7/365 basis and involve multiple scales. The outcome has been the invention of data-intensive science as a fourth paradigm, which has four main activities:

- Capture: How can sensor networks be used to capture geological or ecological data? How can nanotechnology devices be used to gather biomedical data at the individual level?
- Curation: Where and how do we store the data to make it useable?
- Analysis and modeling: How do we mine (i.e., extract useful information) from the data? How can we make inferences without seeing all the data? Can we make models that explain the data?
- Visualization: How does one fully comprehend large data sets? How can we make the human-computer interface more effective?

Computational Science Example

Given these two new paradigms of science, it is important that K-12 educators provide their students with the basic underpinnings of scientific computing and data-intensive science. Let's explore a very simple example to illustrate scientific computing and how technology can give students earlier access to scientific topics than through theory and experimentation alone. The example concerns modeling heat diffusion on a plate using a freely available software package NetLogo. The NetLogo model allows the user to select the plate's material and the temperature conditions on the plate's boundary and then model the diffusion of heat on a plate over time. This allows the user to simulate multiple iterations of the model without knowledge of the heat equation which utilizes partial differential equations (Fig. 1).

By reducing the example into a discrete model where the plate is represented by a 10×10 square (Fig. 1), the concept of heat transfer can be simplified to the level of elementary arithmetic: calculate the average temperature differences around a given node to determine the new temperature of that node. A particle's temperature changes at a rate proportional to the difference between its temperature and the average temperature of its neighbors. For example, if a point P has temperature of 12°, with neighboring points of temperatures 10°, 10°, 20°, and 20°, and the constant of proportionality for heat transfer is 1/3, then point P will have an updated temperature of $12 + 1/3((-2-2 + 8 + 8)/4) = 12 + 1/3(3) = 13$. In the 10×10 model, finding the new temperature at each point is a matter of four subtractions to determine temperature difference and four additions and two divisions to determine a new temperature, a process that can be completed by hand. However, in a 100×100 square, there are 100,000 required calculations per step, and while each step is simple, the number of calculations requires a computer simulation. If we make the grid $1{,}000 \times 1{,}000$ units, the computation requires 100 more calculations per step taking the total number of calculations up to ten million. Expanding this to three dimensions, a cube 1,000 units on each side, requires ten billion operations to calculate the temperature at each node. The necessity of high-performance computers for simulations for even the three-dimensional model is clear.

Education Issues

There are four key elements of why such models are important to student understanding:

1. The dynamic, visual nature of such models
2. The allowance of easy variation of parameters
3. Forced construction of equations out of physical observations
4. Opportunities for a better understanding of orders of magnitude

Computational thinking integrates the power of human thinking with the capabilities of computational processes and technologies. The essence of computational thinking is the generalization of

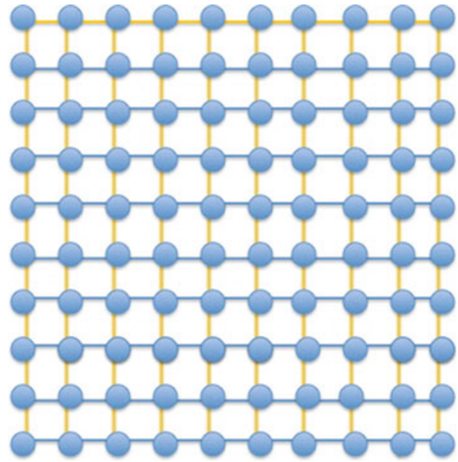
Discovery Science, Fig. 1 Partial differential equations governing heat transfer on a plate

$$\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = k\Delta T$$

$T(x,y,t)$ is the temperature of the point (x,y) at time t,

k is a constant, and

Δ is the Laplacian operator.



ideas into algorithms to model and solve problems. The new paradigm of scientific computing impacts teaching in four distinct ways:

1. Profoundly – never before have two new paradigms occurred within such a short time frame, and we need to think of scientific computing as a fundamental twenty-first-century skill (Wing 2008).
2. Systemically – not as a separate subject area, but as a paradigm relating the interdisciplinary nature of science, engineering, and the humanities. Scientific computing has a symbiotic relationship with mathematics, science, and engineering; computational thinking requires abstraction and the ability to work with multi-layered and interconnected abstractions (e.g., graphs, colors, time); and it draws on "real-world" problems.
3. Vertically – scientific computing must be developed over many years (Pre-K through college) with a need for experiences to be provided early. Examples of vertical strands are provided in Table 1.
4. Wisely – programming should be incorporated at appropriate times. Computational thinking is not just programming or computer engineering; and much of computational thinking can be developed without programming. The emphasis should be on quality, not quantity of experiences, and the experiences must be tied to the thought processes that arise in utilizing a computer to model a system or mine a data set.

Data-intensive science should also inform our teaching. There is a need to provide basic information literacy skills so that students can be productive members of the twenty-first-century workforce and adapt to an increasingly data-dominant world. Teaching should address the following: How is data mining done? How are inferences drawn from large data sets? What are the pros/cons of models? How can one digest data? Teachers need to make learning more authentic. There are a wealth of resources to connect content areas to "real-world" problems. Curriculum needs to have more depth, less breadth. Project-based and place-based learning pedagogies provide a framework for moving toward in-depth learning experiences for students. We need to change the way we "see" and sense data. This can be done by providing student experiences with multiple interpretations and representations, such as 3D, color graphics, and different scales. Interdisciplinary understandings will be essential, since real-world grand challenges must be approached from multiple perspectives. This calls for more integrated curricula that move away from the silo effect where disciplines in schools are isolated from each other. We must help develop new intellectual tools and learning strategies in our students, such as comprehension of the importance of different scales, the understanding of complex systems, and how does one frame and ask meaningful questions, We also need to provide new experiences for the students

Discovery Science, Table 1 Vertical strands of scientific computing (for more details, see http://www.iste.org/learn/computational-thinking/computational-thinking_toolkit.aspx)

Components	Examples
Algorithms	Importance and qualities of algorithms, binary vs. linear search, finding averages independently and in parallel, basic computational algorithms and their efficiency
Modeling	How we get mathematical observations, addition as counting and multiplication as area or repeated addition, graphs as ways to see change, hands-on dynamical systems, relating physical laws to equations, relating change to slopes of graphs, studying complex, multi-agent phenomena
Probability	Understanding of randomness; basic probability concepts; meaning of average behavior, trends; law of large numbers; geometric probability; sampling through random walks; quantification of uncertainty in simulations (use of ensembles)
Decomposition	Breaking down a task or process, doubling methods to multiply, areas via simple geometric subdivisions, steps for solving different types of equations, areas via integration
Complexity	Understanding of interrelationships and complexity, basic cause and effect, sum of parts can be greater than whole, interpretation of graphs, multiple variable interrelationships
Pattern recognition	Multiples, divisibility, triangular numbers, linear-area-volume dynamic change
Abstraction	Pattern generalization, ability to filter out information, ability to generate information needed, making and verifying conjectures, variables

including collecting and interpreting data from sensors, mining data, collaboration in framing and solving problems, conducting interdisciplinary synthesis, using science to inform policy inferences, use of scientific computing, use of data gathering tools, and practice in visualization. Finally, students must be exposed to statistics, with a focus on data-driven problems and understanding statistical concepts.

Cross-References

- ▶ Authentic Science
- ▶ Futures Thinking in Science Education
- ▶ Integrated Science
- ▶ Models
- ▶ Problem-Based Learning (PBL)
- ▶ Representations in Science
- ▶ Science, Technology, Engineering, and Maths (STEM)
- ▶ Transformative Science Education

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Discussion and Science Learning

Lyn Dawes
Cambridge, UK

In memory of Phil Scott

Keywords

Dialogue; Discussion; Exploratory; Interthinking

Learning about science involves asking questions about the world around us and collecting evidence that will help to answer them and then asking further questions. Establishing a theory in science involves people systematically testing their own and other people's ideas to develop robust explanations which fit the evidence. In science, there is never really definitive proof as we might find in mathematics but a gradual working towards a more robust scientific point of view that can explain observations, data, or other evidence. Science learning begins as children question things naturally and draw conclusions from their lived experience. So, a child kicks a ball and notes that it slows as it rolls along the grass and then stops. A reasonable hypothesis for this observation is that the energy put into kicking the ball has been used up. A ball rolling down a hill does not need as much energy because it is easier to go down than up. Similarly a child might notice that the sun is behind nearby trees in the morning, but by lunchtime it is overhead, and that sometimes the sun is yellow, sometimes red. The sun must therefore both move and change color. The use of metaphor, imagery, and imagination in some of our common ways of describing natural phenomena also offers learners a kind of explanation for how things work: for example, "darkness fell," "waves bring the tide up to the top of the shore," "the toy won't work because the battery has run out of electricity."

The outcome of making meaning from a mix of everyday observation and language experiences is that children generate for themselves some work-a-day explanations of the natural world. Such explanations – which may never be articulated – seem to fit what is observed and can last a lifetime. However, assiduous generations of scientists have collected enough information for us to be able to identify some of these ideas as "misconceptions." A ball rolls to a halt under the influence of friction and gravity. Energy cannot be used up. The sun stays in one place while the earth spins; its color is affected by the atmosphere that light passes through to reach us. Batteries contain not electricity but chemicals which can generate electricity. Learning in science must therefore involve eliciting children's already-formed ideas, then providing a range of experience and evidence to help the child to see a different and more scientific perspective if necessary. To consolidate learning, we can enable a child to apply their new knowledge in ways that help them to understand that it is sound and generalizable.

The body of established scientific knowledge, carefully accumulated over the years, is important to us and to the well-being of the earth. It is unnecessary for each child or each generation to repeat the process of finding everything out from scratch. And so an effective education in science involves an intricate mix of activity, discussion, and practical application, including helping children to understand and acquire the relevant skills and the processes scientists go through to ensure that their investigations can be replicated. It involves children in learning both what is established as factual knowledge and the technical language which helps scientists to communicate accurately and concisely with one another. As Jay Lemke puts it, children must become "fluent speakers of science." Science learning necessitates acquiring a collaborative approach and developing the capability to analyze, communicate, and formulate testable questions.

There may be famous scientists who have made strides in establishing science concepts alone; but mostly it is cooperation, discussion, and thinking together that create new ideas. Science is not just factual information and enquiry but also a set of attitudes and values to do with accepting responsibility, being aware of implications of research, and staying open-minded. Einstein, at first completely dismissive of the idea of a Big Bang starting the universe, later gracefully conceded that Hubble's work showed that this was so. Finally, for the teacher, science learning also involves keeping alive the quirky capacity for curiosity and creativity that helps scientists to make the little leaps of imagination – or the seismic shifts – that keep moving human knowledge onwards.

Discussion in Science Learning

Two seminal UK projects in science education of great international influence were the Children's

Learning in Science project (CLIS; University of Leeds) and the Science Processes and Concept Exploration project (SPACE; King's College London and University of Liverpool). The SPACE approach was to "start where the children are," building on the ideas children bring with them to lessons and helping them to develop their understanding of scientific concepts. The CLIS approach involved activity and reflection in which science concepts were tried, tested, and discussed through an imaginative practical approach. Indeed both projects involved science as a practical subject and foregrounded the role of teachers in engaging, motivating, and stimulating the curiosity of children while providing them with a solidly scientific perspective on the world around us. Both have left a valuable legacy of theory and practice for science teachers. In addition another UK project, the CASE (Cognitive Acceleration through Science Exploration) project (King's College, London), was built on a teaching approach involving metacognition, that is, children's reflection on their own thinking. This has been shown to have a marked impact on cognitive development and academic achievement. Primary science education in the UK was given a boost with the introduction of the National Curriculum in 1995 when it was established as a core subject and allocated equal time with English and mathematics. Subsequent revisions of this curriculum have meant that schools have allocated more priority to English and mathematics, at the expense of other subjects. The 2014 National Curriculum highlights the importance of teaching a scientific understanding for our children and strongly suggests that teaching strategies should involve discussion which enables children to ask their questions and talk through tentative ideas.

Both primary and secondary science classrooms in many parts of the world have in the past been characterized by their quietness; teachers were often evaluated by the noise level of their classrooms, silence being highly rated and children's talk being frowned upon. However, the influence of a sociocultural approach to learning has led teachers, particularly primary teachers, to feel that it is quietness that should cause unease rather than noise, at least if it is the dominant mode of the classroom. Learning is today understood to be social. The child's first and best means of communication is through spoken language. The Russian psychologist Lev Vygotsky and the translators and interpreters of his work have helped educators to feel confident that encouraging children to talk in class is of great benefit to their learning. Vygotsky noted that language offers tools with which ideas can be shaped and articulated, then offered for joint reflection. Once aired, ideas can become part of the shared understanding of a group, available for discussion and modification. Being part of a group talking about ideas in science allows individuals to internalize ideas, reflect on them, and bring their modified thoughts to subsequent discussion. Jerome Bruner realized that children in a classroom can be one another's best resource if they can communicate their thoughts through such discussion. Talk offers the chance to share understandings of scientific phenomena and come to a larger consensus or a productive disagreement. Either such consensus or disagreement can help to establish a robust theory or a new line of enquiry.

In his extensive listening to students talking in groups, the educational researcher Douglas Barnes noted that spoken language enables the individual, and the group, to begin to organize ideas. Talk may be hesitant as ideas are proffered and considered; contributions may be incomplete and tentative. Barnes saw that what he termed "exploratory talk" was of great value in aiding understanding and allowed children to express knowledge, opinion, and uncertainty. Importantly, he recognized that if groups of children were to achieve such effective discussion, their talk together must be of a specific quality, a different type of talk than their usual more casual interaction with one another, and so raising their awareness of discussion as a tool for learning would mean that group work became more reliable and effective. He identified a type of talk in which children tentatively try out their own ideas in comparison with the views of others. He suggested that children should be encouraged to contribute ideas from their own experience and to suggest where there seemed to be discrepancy between points of view. In addition, Barnes advocated encouraging children to ask productive questions and noted that it would be invaluable if students were taught how to elaborate on their initial ideas. Discussion in science classrooms should draw on these ideas to ensure that science teaching is inclusive, starts with the child, and develops both science knowledge and understanding.

Every child can communicate, and almost all have a range of talk repertoires at their disposal. Children switch between talking in a range of contexts such as the playground, at home, during competitive sport, in class, and so on. They can also talk to adults appropriately and are able to use their individual accents and dialects to communicate fluently. Each of these types of talk is of equal value as the child functions in their social world. Each type of talk, including classroom science discussion, is based on some implicit, straightforward, but essential "ground rules." Ground rules are the usually hidden ways that people devise to organize themselves so that social harmony is possible. Ground rules for discussion in class are different from the ground rules, for example, of playground talk, talk between children and their parents, or talk between children playing a collaborative game.

Neil Mercer and Rupert Wegerif, in studying children talking about science at computers, found that some children were unaware of the ground rules for exploratory talk. Group work ended in disharmony, and learning fell away as disputes arose which could not be resolved, or groups simply agreed with initial suggestions and did not seek understanding. It was apparent that some children had no experience of a reasoned, exploratory discussion. In learning terms, this is analogous to only having heard traditional stories and never having experienced science fiction, or a ghost story, or a mystery story. It is simply a gap in experience which can be addressed by teaching. Other children were aware of the ground rules which could help them to think and learn together but were unable to apply them. Still others felt that sharing their knowledge and understanding would diminish their personal status – everyone would "know" as much as they did. The ground rules for exploratory talk as later elaborated by Neil Mercer can be summarized as listen to and include everyone, ask questions, challenge what you hear, give explanations with reasons and elaborate on your ideas, and seek to reach a negotiated agreement. The discussion, creation, and use of a class set of "ground rules for exploratory talk" helped children to see that sharing learning does not make individuals poorer but makes the group richer and that exploratory talk could help everyone to articulate their ideas and could help individuals, groups, and the class to establish a joint, robust scientific point of view.

Substantial work elaborated in a number of other entries in this encyclopedia has been able to provide examples which better establish Vygotsky's ideas, left as hypothetical by his untimely death, and thus contributed to educational theory in science learning. For example, Vygotsky saw individual thought as a product of reflection; spoken language he describes as allowing intermental ("between minds") thinking and drawing on intramental ("within the mind") or individual thought. He postulated that adults talking to children in an exploratory way – though he didn't use that term – would be able to influence their thinking. That is, intermental thinking influences intramental thinking; but crucially, that subsequent talk could draw on the newly developed thinking of individuals, contributing to the group's subsequent better understanding. Discussion like this, Vygotsky argued, creates a spiral of learning, as individual development supports group thinking which in turn aids individual understanding and so on. This spiral has been observed, for example, in samples of children's talk about science collected in the Thinking Together project, so confirming Vygotsky's hypothesis. For science learning, this means that children, engaged in a combination of science activity and discussion based on exploratory talk, can learn from and with one another and can construct new knowledge together in a way that is accessible to all of them.

In addition, by engaging in exploratory talk in science, children are learning in effect "how to discuss." They become more adept at listening actively, asking pertinent questions, providing reasons for their contributions, weighing up and summarizing what has been said, and coming to an agreement together or establishing new questions together. This is a transferrable skill and is the basis for rationality, teamwork, and social learning. Neil Mercer has described the joint reflection generated when members of a group engage one another in exploratory talk as "interthinking." Interthinking is a powerful way for groups to proceed during enquiry, problem solving, and understanding new ideas not only in science but across the curriculum. Science learning in classrooms therefore requires carefully organized group work based on the direct teaching of the skills of exploratory talk, the establishment of relevant ground rules for discussion, and in helping children to see how and why to engage in interthinking.

Dialogic Teaching in Science

Relevant science learning involves the teacher enabling children's access to current scientific thinking. Traditionally this has involved such strategies as chalk-and-talk and the completion of "worksheets." More recently the idea of "dialogic teaching" has described how science teachers can engage children in whole-class debate about their ideas in science. Dialogic teaching as described by Robin Alexander involves teacher and class in a searching, cumulative debate, orchestrated by the teacher. During dialogic teaching, children take extended turns, explaining what they know or do not know, and responses are chained together in a meaningful way, stimulating further contributions. It is worth noting that there are clear links between the spoken language structures of dialogic teaching and those of exploratory talk, that is, teachers who generate dialogue are teaching children how to talk effectively to one another in groups.

A distinctive feature of dialogic teaching is that it involves teachers asking authentic questions (as opposed to the common classroom practice in which teachers ask questions to which they already know the answer, in order to involve children or to check knowledge items, for example, *Teacher*: What do we call the ends of magnets? *Child*: Poles. *Teacher*: Yes, that's right).

In dialogic teaching, answers are much less predictable and less likely to be a single word, and any child can answer, not just those who choose to put up their hand. The teacher keeps the discussion open. If the above example of closed and conventional questioning is recast as it would be in dialogic teaching, it would be something like the following:

> *Teacher*: What sort of magnets do you think are strongest?
>
> *Child*: My brother has some you throw up in the air, and they stick and make a funny noise.
>
> *Child 2*: The horseshoe magnet, the red one, it's big, but it's rubbish with the paper clips.
>
> *Teacher*: Anyone else with information about horseshoe magnets?
>
> *Child 3*: The ends both pull together, they – it doesn't mean it's strong, you even get them at playgroup.

In elaborating the idea of dialogic teaching, Phil Scott established that learning in science classrooms proceeds through different episodes of talk as a lesson unfolds over time. He recognized that if children are to have access to a scientific point of view, the teacher must at times establish what is already known by providing an authoritative account of factual information. Phil Scott showed how a timely combination of demonstration, clear teacher explanation, and the active involvement of students provides powerful contexts for classroom learning in science. For example, he showed students a tank of water standing on a table and asked for their ideas about what forces were at work. He asked them to consider whether the table exerts an upward force. Their uncertainty about this was resolved by asking them to take the place of the table and hold up the tank – or holding it up himself and showing what happened if the upward force was removed. He established that science teaching over the time span of a lesson, or series of lessons, proceeds through episodes that are more or less dialogic or authoritative in their nature – his insight being that authoritative episodes, where children are told things directly, are a crucial part of an ongoing dialogue. He recognized that teachers have the professional expertise to create lessons which draw on a range of strategies appropriate to the learning needs of the students, referring to this as "highly skilled guidance" in both discussion and science content.

The concept of "communicative approach" was first introduced by Eduardo Mortimer and Phil Scott to describe how a teacher works with children develop ideas in the classroom. The communicative approach is defined by characterizing the talk between teacher and pupils along each of two dimensions: interactive-noninteractive and dialogic-authoritative.

Interactive teaching involves talk between teacher and students, while noninteractive teaching involves only the teacher's voice. Dialogic teaching involves the teacher asking students for their points of view and explicitly taking account of them, asking for further details, or noting them for further consideration. In dialogic talk, there is always the attempt to acknowledge the views of others, and through dialogic talk the teacher attends to the students' points of view as well as to the scientific explanation.

During science sessions, a shift from dialogic to authoritative approach constitutes a "turning point" in the sequence of episodes. Phil Scott and Jaume Ametller showed how part of a teacher's professional expertise is to recognize key moments and carefully close down dialogic interactions. They could then provide a more authoritative, scientific point of view at times when it was clear that students were ready for an explanation of phenomena or an answer to the questions they had raised. Subsequent discussion in groups enabled students to talk about their new thinking and to examine the fresh perspective they had been given, in order to test its explanatory power, and to use appropriate vocabulary in ways that would support concept formation.

Science Concepts and Concept Formation

A child might know that sand is runny when dry and sticky when wet, without being able to say why. Some may not question this difference. But if asked, "Why do you think wet sand is sticky?" children will create everyday explanations drawing on their current vocabulary, experience, and creative imagination. A scientific explanation involves the concept of surface tension, an understanding of which requires learning about the molecular structure of water, hydrogen bonds, a consideration of particle size, and perhaps some thinking about gravity. Concepts are ideas created in our minds from various items of information and understanding. The label "surface tension" is in essence technical/scientific shorthand for a complicated chemical and physical effect. However complex the phenomenon, its outcomes – making sand sticky, making water droplets form – are easy to access and describe. The child may begin to use the label "surface tension" and only subsequently gradually accumulate the experience and information which deepen understanding. Concept formation is not an instantaneous effect but a gradual reconsidering and reshaping of ideas in the light of experience – and in the light of discussion with others.

This is a perennial dilemma for science educators – whether first to introduce accurate vocabulary so that experience is more readily describable or whether to first provide opportunities and experiences and only later provide the vocabulary necessary for explanation and concept formation. For example, a child might look at plant cells through a microscope and describe them as squares or rectangles. Another child might say bricks or boxes, and so the chance to talk about the three-dimensional nature of plant cells arises. The idea that living things are constructed from cells is fundamental to biology, and children have to start somewhere in learning this by observing cells. Whether we call them that at first seems to be a matter of opinion, based on the teacher's learning aim for their session. It is also important to note the metaphorical power of words – cells were named after the small rooms inhabited by monks. The chance to use the word "cell" aloud and in a science context, with other learners, provides invaluable practice and generates confidence.

The overlap between science terms and everyday uses of the same word can create confusion; for example, the commonly used words *energy* and *force* have particular technical meanings in science. Discussion of what is understood by particular vocabulary can help children to acquire a more scientific perspective as learning proceeds. Another example is the term *liquid*; this has a specific scientific definition, but young children may think that a liquid is sticky (washing up liquid). Similarly they may refer to any colorless liquid (e.g., molten candle wax) as water.

For individuals, science education proceeds both in startling leaps and in lengthy times of reflection and, seemingly, forgetting. But the ideas and words are held in mind and catch on the hooks offered by life – in and out of school. Learners may use new vocabulary in relevant contexts to build up an understanding of some important concepts or draw on their learning in what might seem unrelated contexts. So, if, for example, we consider teaching the concept "Waves have energy," it is possible to consider how a mix of activity, information, and discussion can provide an environment in which learners create this concept in their own minds. Allowing time for the mind to assimilate, try out, and integrate new ideas is crucial. It is also important to note that concepts like this can be taught to learners of any age. Bruner (1960) has written "You can teach any child any subject at any age or stage of development in an intellectually honest way." In primary settings, guided play, purposeful creativity, and chances to talk are the keys to tapping into children's interest in the world around them and helping them establish science concepts.

Analogies are widely used to explain and clarify science concepts, for example, considering current electricity to be analogous to a moving bicycle chain, a hosepipe filled with water, sweets passed around a circle of children, or a loop of rope running through their hands. No one analogy has complete explanatory power – no analogy can logically be exactly the same as the phenomenon it is held or relate to, but a range of analogies gives a concrete anchor for abstract ideas and therefore makes the abstraction more understandable.

With increasing understanding comes the opportunity to develop increasing complexity and to use other modes of communication, further specialized language, mathematics, and a range of ways to present data. Essential to science learning is an ability to communicate understanding to others so that knowledge is shared for further use. Without Newton's mathematical and verbal description of the forces that shape the universe, there would be no basis for Einstein's subsequent review and rethink of what we know about how the planets move. Without Einstein's ability to communicate his ideas to others – in 1905 he published three physics papers on the reality of atoms, the photoelectric effect, and on special relativity – his new explanations would not now be a basis for contemporary science thinking.

Summary

The careful accumulation of science knowledge has enabled us to understand more and more about how the world works. Because of this, we are no longer at the mercy of explanations of the natural world which are to do with imagination, superstition, or magic. The problems that can arise from applications of science, for example, in warfare, food production, human reproduction, and excessive global warming, are to do with human choices about how we use our knowledge, not the science itself. A sound science education is the right of every child. Through their learning of science, young people gain the opportunity to consider facts, issues, and ideas and learn how and why to discuss current causes of concern or interest with others. A discussion-focused approach to science education can support the child's development of concepts while teaching them how to take part in reasoned debate. Asking questions is natural. Science teaching can help young people to learn to collect evidence, to keep their curiosity alive, and to respect the world we all depend on.

Cross-References

▶ Alternative Conceptions/Frameworks/Misconceptions
▶ Cognitive Acceleration
▶ Conceptual Change in Learning
▶ Constructivism
▶ Dialogic Teaching and Learning
▶ Discourse in Science Learning
▶ Heterogeneity of Thinking and Speaking
▶ Socio-Cultural Perspectives on Learning Science

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