Third Misconceptions Seminar Proceedings (1993)

Paper Title: The Role of Research on "Misconceptions and Educational Strategies" in Developing Benchmarks for Science Literacy
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Keywords:
General School Subject:
Specific School Subject:
Students:

Macintosh File Name: Kesidou - Science Literacy
Release Date: 9-18-1994 I

Publisher: Misconceptions Trust
Publisher Location: Ithaca, NY
Volume Name: The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics
Publication Year: 1993
Conference Date: August 1-4, 1993
Contact Information (correct as of 12-23-2010):
Web: www.mlrg.org
Email: info@mlrg.org

A Correct Reference Format: Author, Paper Title in The Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Misconceptions Trust: Ithaca, NY (1993).

The Role of Research on "Misconceptions and Educational Strategies" in Developing Benchmarks for Science Literacy

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ABSTRACT

This paper addresses the relationship between research on misconceptions (and educational strategies) and the development of Project 2061 benchmarks for science literacy. The benchmarks specify a sequence of steps through which students would be expected to progress to reach desired outcomes specified for high school graduates in Science for All Americans. Benchmarks result from a process Project 2061 calls "back-mapping." "Back-mapping" involves considering what the component ideas are for a particular learning goal, then imagining lower levels of sophistication at which these ideas might be understood at earlier grade levels. Benchmarks reflect the logical structure of science and an understanding of student learning, gleaned from teachers' experience as well as from research into how children learn. Because such research is limited in many areas, developing benchmarks is a specially difficult task. Kinds of research proving most useful and further research needed in developing and revising benchmarks and curriculum based on them will be identified.

INTRODUCTION

Project 2061's *Science for All Americans (SFAA)* specified literacy goals in science, mathematics, and technology for all high-school graduates (Rutherford & Ahlgren, 1989). During the past four years, Project 2061 has been working to develop science literacy benchmarks for grades 2, 5, 8, and 12. The benchmarks propose a sequence of steps through which students might progress to reach the *SFAA* goals. They are inferred from the learning goals within *Science for All Americans* and from knowledge about how students learn. Benchmarks are intended primarily as a guide in developing curriculum. They can help educators make choices about what to eliminate from the curriculum as well as what to include.

Benchmarks result from a process Project 2061 calls "back-mapping." In "back-mapping," educators think through the flow of learning -- from the time students enter kindergarten until they graduate from high-school -- and identify carefully the conceptual building blocks needed to achieve each particular learning goal stated within *Science for All Americans*. Back-mapping involves considering what the component ideas are for a particular *SFAA* learning goal; identifying what prerequisites are needed for understanding these component ideas; imagining lower levels of sophistication at which component ideas and their prerequisites might be understood at earlier grade levels; and estimating the approximate grade placement for each idea (Figure 1). Typically, when maps are constructed, connections between *SFAA* topics become apparent: Several ideas from different topics are often required to understand a subsequent idea, and several ideas depend on one prior idea (Figure 2).

Maps reflect both the logical structure of science and an understanding of student learning, gleaned from teachers' experience as well as from research into how children learn. Because such research is limited, back-mapping is a specially difficult task. For example, only occasionally is there research available on what low level sophistication ideas are like or on how the level of sophistication can be increased. Further complicating the effort is the need to consider not only what students know, but what they might know if they had been taught differently from the beginning.

This paper addresses research issues that emerge from Project 2061 "back-mapping" efforts. These efforts highlight the need for further research to guide the process of developing benchmarks. Kinds of research proving most useful and further research needed in developing and revising benchmarks are identified.

CATEGORIES OF RESEARCH FINDINGS

Research findings about whether students can understand an idea fall into one of several categories.

(1) Students do understand the idea without any instruction at all, or after traditional instruction at grade N.

(2) Students do <u>not</u> understand the idea without instruction at grade N.

(3) Students do <u>not</u> understand the idea after traditional instruction at grade N. (Traditional here means instruction that does not explicitly take students' conceptions into account.) So the idea may be intrinsically too sophisticated for the grade level or may not have been adequately prepared for. The

research may reveal the kinds of difficulties students have and hence what it may take to build cases that would be convincing to them.

(4) Students do understand the idea after special instruction at grade N.

(5) Students still do not understand even after the special instruction at grade N. The idea has to be simplified, better prepared for, or postponed until students are more ready.

THE ROLE OF RESEARCH IN DEVELOPING BENCHMARKS

These research findings can inform the development of benchmarks in one of several ways.

Identifying prerequisites for learning goals

Research may confirm prerequisites which were identified based on logical considerations; point to prerequisites, which, although could be identified logically, all too often are mistakenly considered as simple and self-evident; or may suggest prerequisites that cannot be derived only on the basis of logical considerations. For example, the published research on students' understanding of evaporation and of astronomy was very helpful in identifying the prerequisites for the eventual goal understandings of explanations of celestial phenomena (see Figure 3) and for the water cycle (see Figure 4).

Explanations of celestial phenomena. Research suggests that explanations of the day-night cycle and the phases of the moon are very difficult for students. To understand explanations of the day-night cycle, students need the idea of a spherical earth, itself a challenging task. Students cannot believe in a spherical earth without some knowledge of gravity to account for why people on the "bottom" do not fall off. Nor can they accept that gravity is center-directed if they do not know the earth is spherical (Nussbaum, 1985a; Vosniadou, 1991). Taking this into account, *Benchmarks for Science Literacy* recommends teaching the concepts of the earth and gravity in close connection to each other and only then teach explanations for the day-night cycle.

Instruction on the phases of the moon often takes for granted that students know that we see things by reflected light - but they do not (Vosniadou, 1991). In addition, research confirms the logical notion that students cannot understand such explanations before they reasonably understand the relative size, motion, and distance of the sun, moon, and the earth (Sadler, 1987; Vosniadou, 1991). Taking this into account, *Benchmarks* recommends that students should understand that the moon reflects light from the sun before they explain the phases of the moon. In addition, *Benchmarks* recommends that students make physical models that represent the sun-earth-moon relationships.

Water cycle. Research confirms the logical notion that understanding the water cycle requires understanding conservation of matter, evaporation, condensation, clouds, and rain. Many students must traverse a series of stages to understand evaporation. Before they understand that water is converted to an invisible form, they may initially believe that when water evaporates it ceases to exist, or it changes location but remains a liquid, or it is transformed into some other perceptible form (fog, steam, droplets, etc.) (Bar, 1989; Russell, Harlen, & Watt, 1989; Russell & Watt, 1990). Identifying the air as the final location of evaporating water and accepting the existence of invisible vapor requires that students first accept air as a substance which exists permanently and not only when it is in motion. Students cannot understand rainfall before they overcome their misconception that something whose weight they can't feel (for example, a small droplet of water) has no weight (Bar, 1989).

Taking these research findings into account, *Benchmarks* recommends that students become initially familiar with phenomena that will in time contribute to their understanding of evaporation, condensation, and the conservation of the amount of water by weight. For example, students who believe that water from a container disappears because it penetrates solid objects may be challenged by observations that "water left in an open container disappears, but water in a closed container does not disappear." Or, experiences that suggest a connection between liquid and solid forms of water, for example "If water is turned into ice and then the ice is allowed to melt, the amount of water is the same as it was before freezing" may be a first stepping stone toward students' understanding the conservation of the weight of water during phase changes. *Benchmarks* also recommends that students should understand that "air is a substance that surrounds us, takes up space, and whose movement we feel as wind"; "when liquid water disappears, it turns into a gas (vapor) in the air and can reappear as a liquid when cooled"; "clouds, like fog and "steam" from a kettle, are made of tiny droplets of water"; and "no matter how parts of an object are assembled, the weight of the whole object made is always the same as the sum of the parts; and when a thing is broken into parts, the parts have the same total weight as the original thing" before they learn how "water evaporates from the surface of the earth, rises and cools, condenses into rain or snow, and falls again to the surface."

In addition to considerations based on the logical structure of science and on how students learn specific scientific ideas, identifying prerequisites for learning goals involves two additional considerations (see also Ahlgren, 1993). Learning goals that involve explanations may benefit from first being familiar with a critical mass of phenomena that the explanations can account for. This consideration is consistent with conceptual change theories which suggest that it is necessary for students to see "fruitfulness" in changing to scientific thinking (Posner, Strike, Hewson, & Gertzog, 1982). Learning goals that involve explanations may benefit also from building on relevant analogies. Much of explanation in science and science learning involves analogies to what the scientist or the learner already knows. Although learning research suggests some general guiding principles for selecting effective analogies (see for example, Brown & Clement, 1989), specific research is needed to assess the value of recommended analogical precursor ideas.

Specifying lower levels of sophistication at which learning goals in Science for All Americans might be understood

For example, research suggests the notion of "fair comparisons" can be viewed as a lower level of sophistication at which the notion of "controlled variables" can be understood already in the earlier elementary grades (Wollman, 1977a, 1977b; Wollman & Lawson, 1977). However, while young children have a sense of what it means to make fair comparisons, they frequently cannot identify all of the important variables. Taking this into account, *Benchmarks* recommends that students can "recognize when comparisons might not be fair" (grade 5) before they can understand that "if more than one variable changes at the same time in an experiment, the goal of the experiment may not be clearly attributable to any one of the variables" (grade 8).

Learning research also provides general guiding principles for stating less sophisticated precursors of an idea. For example, research indicates that qualitative ideas are more closely connected to students' prior knowledge than their quantitative counterparts and that they form the basis for later quantitative understanding. At several places *Benchmarks* recommends teaching qualitative versions of an idea before more sophisticated quantitative versions of the same idea. For example, in the case of energy conservation, *Benchmarks* recommends that students can understand that "whenever some energy shows up in one place, some will be found to disappear from another" (grade 8) before they can understand that "whenever the amount of energy in one place or form diminishes, the amount in other places or forms increases by the same amount" (grade 12).

Placing benchmarks at appropriate grade levels

If research indicates that students understand an idea at a certain grade, with or without special instruction, obviously it can be learned at that level (see categories of research findings 1 and 4 above). If research implies learning difficulties resistant to change (see categories of research findings 3 and 5 above), in many cases learning goals are restricted accordingly. However, in some cases it is proposed that students could learn the targeted concepts or skills at a particular grade span if they had received special instruction (for findings within category 3) or if they had been instructed properly from the start (for findings within category 5). Typically, the sequence clues from research appear to be more reliable than the placement clues, which are often influenced more by current limitations of practice. Consider the following examples.

Atomic theory. Research suggests middle- and high-school students typically have some entrenched misconceptions about atoms that must be overcome (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Nussbaum, 1985; Brook, Briggs, & Driver, 1987). Taking this into account, *Benchmarks* recommends a variety of preliminary experiences and macroscopic ideas about substances and their combinations through grades 5 and 6 as a foundation for an introduction to atomic theory in grades 7 and 8 and a more complete treatment in high school.

Explanations of celestial phenomena. By grade 5, students are able to understand the prerequisites for explaining the day-night cycle. For example, with special instruction, students can understand basic concepts of the shape of the earth and gravity by grade 5 (Nussbaum, 1985a). Taking this into account, *Benchmarks* recommends that students should understand that "the rotation of the earth on its axis every 24 hours produces the night-and-day cycle" by the end of the fifth-grade. By contrast, the prerequisites for understanding the phases of the moon appear to be more difficult for students. For example, elementary school students do not have a notion of light as something that travels from one place to another, and the conception that the eye sees without anything linking it to the object persists after traditional middle-school instruction in optics (Guesne, 1985). Taking this into account, *Benchmarks* recommends that the explanation for the phases of the moon should wait until the end of the eighth grade (see Figure 3).

Water cycle. As noted earlier, understanding of the water cycle requires understanding of evaporation, condensation, rain, and conservation of matter. Research suggests understanding of these component ideas is unlikely before the late middle-school grades. Students understand rainfall in terms of gravity acting on water droplets in early middle-school (Bar, 1989), and the mechanism of condensation in terms of convection and conservation of matter by weight in processes that involve gases in late middle-school (Bar, 1989; Stavy, 1990). Taking this into account, *Benchmarks* recommends that understanding of the entire water cycle should not be expected before the end of the eighth grade.

However, students can start understanding ideas about evaporation, condensation, and clouds, and conservation of matter during the elementary grades. Many students in the 5th grade accept air as a permanent substance, think that clouds contain droplets of water (Bar, 1989; Sere, 1989) and, with special instruction, identify the air as the location of evaporated water and accept that when liquid water disappears, it is possible to get the water back again (Russell & Watt, 1990). However, understanding that water changes into an imperceptible form appears to be difficult for upper elementary students even after instruction (Russell & Watt, 1990; Stavy, 1990). Thus, although the 5th grade benchmarks "air is a substance that surrounds us, takes up space, and whose movement we feel as wind," and "clouds, like fog and 'steam' from a kettle, are made of tiny droplets of water" (Figure 4) are achievable at the fifth grade, the lack of long-term teaching interventions makes it difficult to decide whether students can understand that "when liquid water disappears, it turns into a gas (vapor)" by the end of the fifth grade.

LIMITATIONS OF RESEARCH

Research on students' learning in science and mathematics offers little evidence on many of the topics that are addressed in *Benchmarks*. For one thing, the total number of concepts and skills investigated is still small and unevenly distributed among different content areas. For some topics, such as the structure of matter or force and motion in the physical sciences and computation skills in mathematics there is a rich and growing literature on student learning. For other topics, especially those in the life sciences and social sciences there is little learning research.

Although the available research has given us valuable insights into students' understanding of science and mathematics, how content should be sequenced to build upon students' understanding is a complex issue. For example, should the recommended progression of understanding be patterned along the lines of observed levels of student development? In other words, should we teach intentionally the less sophisticated and sometimes erroneous ideas or strategies of each succeeding level? Or, should we skip the intermediate levels and attempt to teach the most advanced ideas and strategies? Instruction that explicitly moves students through successive stages in the development of basic concepts and skills in arithmetic has shown some success (Case, 1983). However, other studies have successfully based instruction on some of the most sophisticated strategies observed in students' solutions (Romberg & Carpenter, 1986).

The published research has focused on what students do or do not understand at isolated points in time. Sometimes (especially in social sciences and mathematics) there is evidence on how concepts develop naturally (without formal instruction) in students. For example, students are often shown to go through a series of levels to understand a certain idea or master a certain skill. Although such research may provide some guidance for sequencing ideas, tying these ideas to particular grade levels is difficult. For example, research suggests students' ideas about the nature of knowledge and how knowledge is justified develop through stages in which knowledge is initially perceived in terms of "right-or-wrong," then as a matter of "mere opinion," and finally as "informed" and supported with reasons (Kitchener, 1983; Perry, 1970).

This research provides some guidance for sequencing the benchmarks about the nature of scientific knowledge. For example, it suggests that students, before they abandon their beliefs about knowledge being either "right" or "wrong," may not understand that scientists can *legitimately* hold different explanations for the same set of observations. However, this research does not say when, how quickly, and with what experiences students can move through these stages if given adequate instruction. Several studies show a large proportion of today's high-school students are still at the "right-or-wrong" stage of the development (Kitchener, 1983; Kitchener & King, 1981). Further research is needed to specify what high-school graduates could understand, if from a young age they were taught that different people will describe or explain events differently, and that opinions must have reasons and can be challenged on rational grounds.

Little research has focused on instructional interventions that attempt to improve students' understanding. Existing studies with interventions are of rather short duration -- from three weeks to a semester at maximum. These often show limited success in improving students' ideas. However, improved understanding of students' conceptual difficulties through studying interventions can lead to the development of better instructional examples focusing on these difficulties, which in turn can lead to increase in the effectiveness of the intervention (see for example Brown & Clement, 1992). Unfortunately, intervention studies are rarely replicated and the instructional strategies used are rarely refined based on initial results. Without research evidence from carefully designed interventions over longer periods of time, it is difficult to decide whether students can or cannot understand a particular idea at a specified grade range.

NEEDED RESEARCH

A review of the "Misconceptions" literature indicates that the topics investigated are often chosen without regard for their role in understanding the most important ideas in science. For example, considerable research attention has been given to students' understanding of series and parallel circuits. By giving priority to domains of understanding that have been identified as central in *Science for All Americans*, the coherence and utility of the research might be increased considerably.

Even within *Science for All Americans*, ideas are not of equal importance. As noted in the introduction, the mapping of *SFAA* goals and the development of benchmarks revealed some ideas or precursors that would have big payoffs because they are common to many other ideas. For example, the mapping process revealed that some understanding of systems (for example, considering a system's inputs and outputs) is necessary for understanding the ideas of conservation of matter and energy, which in turn is necessary for understanding a variety of phenomena within the physical setting and the living environment. Moreover, research suggests that an understanding of systems may facilitate students' learning in several content-specific areas: Several student misconceptions appear to arise from their inclination to interpret phenomena in terms of absolute properties or qualities ascribed to objects rather than in terms of interactions between elements of a system (see for example, Driver et al., 1985; Brosnan, 1990). Despite its importance, we know very little about what students know and how they can learn about systems.

Benchmarks can be viewed as hypotheses to be confirmed or refuted by further evidence from instructional interventions. Developmental (longitudinal) studies are needed to assess whether the precursor ideas invented for *Benchmarks* are useful. Extended efforts that build on conceptual precursors over several years are needed to determine whether students can indeed learn ideas at the grade ranges recommended by *Benchmarks*.

More generally, research is needed to identify what kinds of sequences are most effective in helping students develop their ideas in science and mathematics. Intermediate ideas should be sought that can be developed in the context of experiences in which these ideas "work." The challenge is then how to move students from the intermediate conception to the goal conception. A possible approach would be to present students with experiences in which these "intermediate" ideas "do not work."

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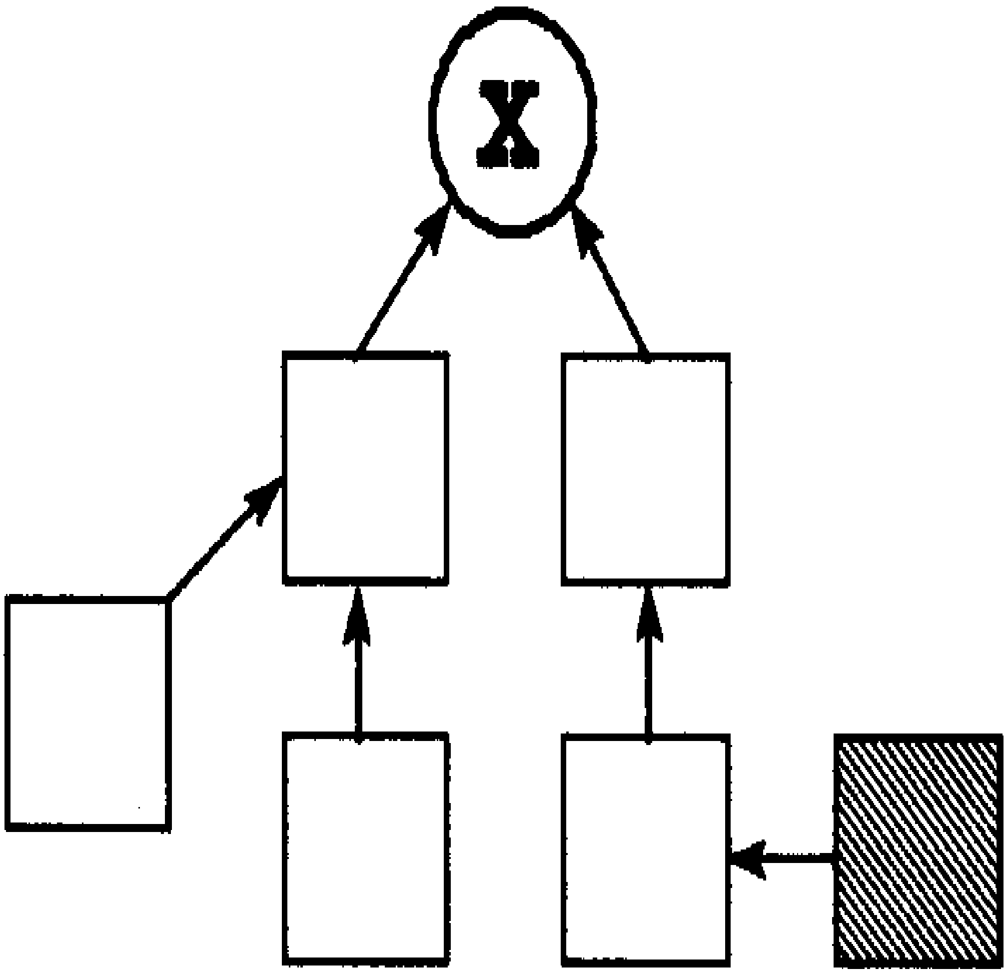
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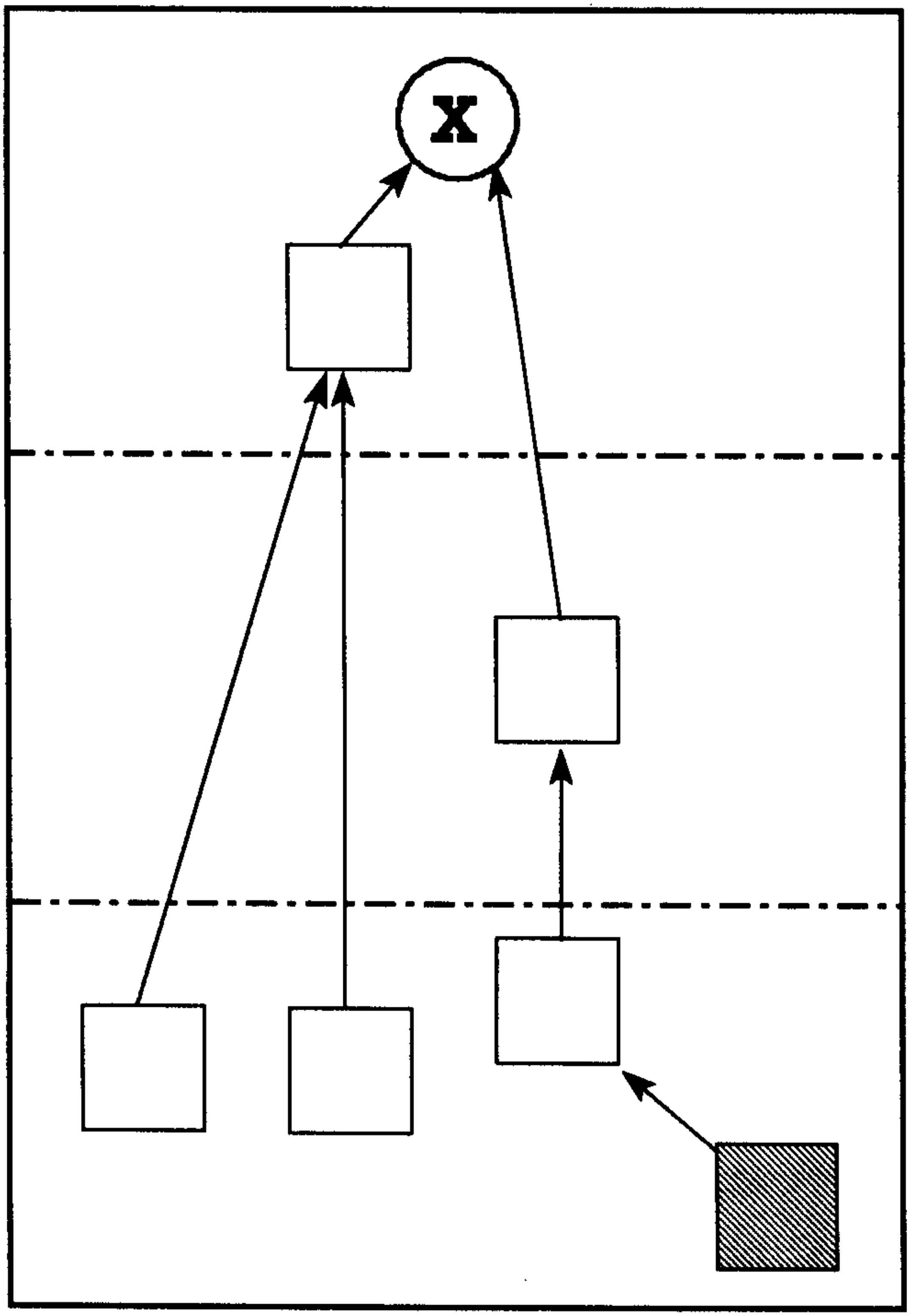

Figure 1. Identifying prerequisites and estimating grade placements.

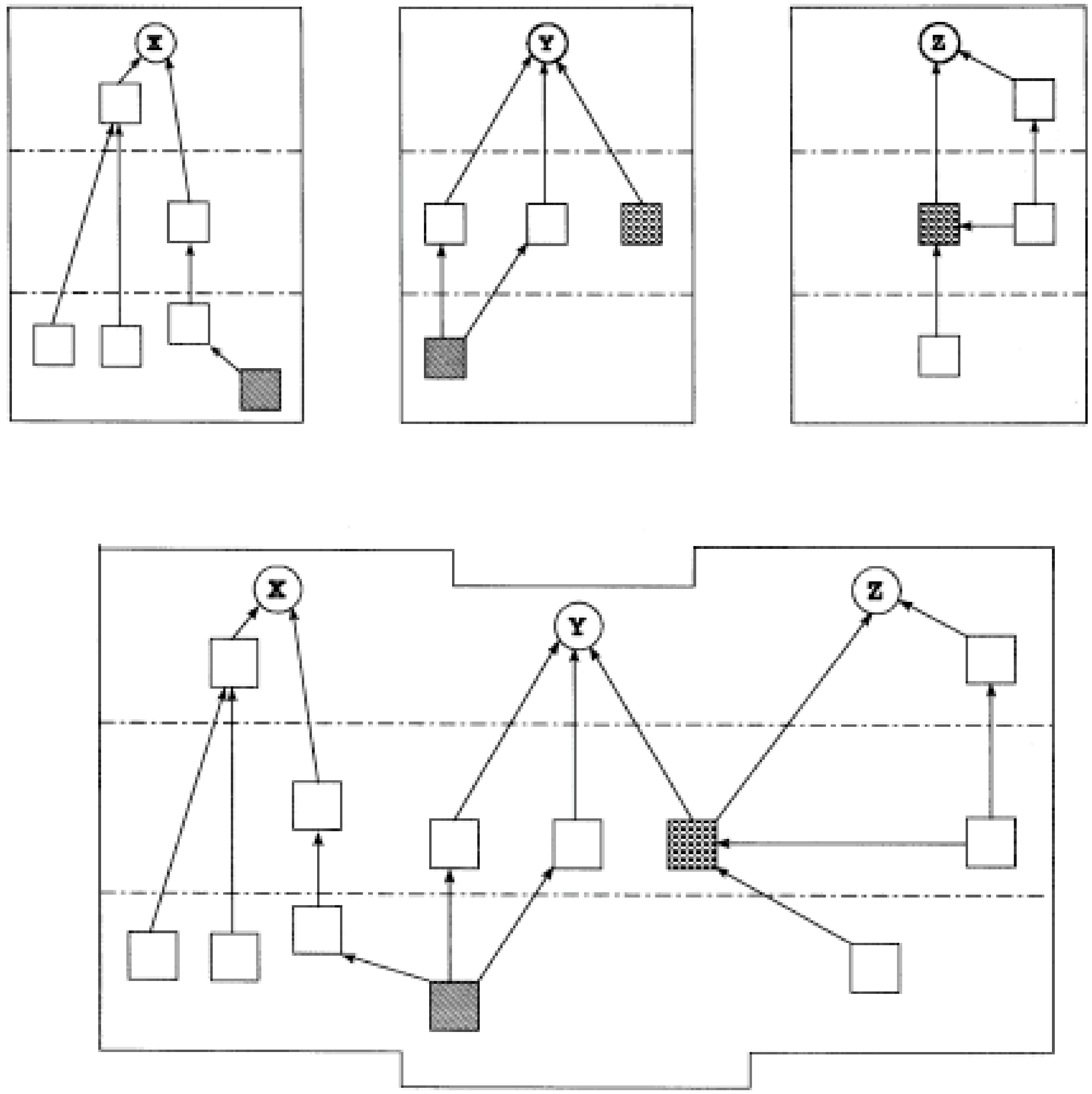

Figure 2. Finding connections between topics.

The motion of the earth and its position with regard to the sun and the moon have noticeable effects. The earth's one-year revolution around the sun, because of the tilt of the earth's axis, changes how directly sunlight falls on one part or another of the earth. This difference in heating different parts of the earth's surface produces seasonal variations in climate. The rotation of the planet on its axis every 24 hours produces the planet's night-and-day cycle - and (to observers on earth) makes it seem as though the sun, planets, stars, and the moon are orbiting the earth. The combination of the earth's motion and the moon's orbit around the earth, once in about 28 days, results in the phases of the moon (on the basis of the changing angle at which we see the sunlit side of the moon (*Science for All Americans*, p. 38).

By the end of the 2nd grade, students should know that:

- The moon looks a little different every day, but looks the same again about every four weeks.
- The sun can be seen only in the daytime, but the moon can be seen sometimes at night and sometimes during the day. The sun, moon, and stars all appear to move slowly across the sky.

By the end of the 5th grade, students should know that:

- The earth is one of several planets that orbit the sun, and the moon orbits around the earth. (4B)
- Things on or near the earth are pulled toward its center by gravity.
- Like all planets and stars, the earth is approximately spherical in shape.
- The rotation of the earth on its axis every 24 hours produces the night-and-day cycle. To people on earth, this turning of the planet makes it seem as though the sun, moon, planets, and stars are orbiting the earth once a day.

By the end of the 8th grade, students should know that:

- Something can be "seen" when light waves emitted or reflected by it enter the eye—just as something can be "heard" when sound waves from it enter the ear.
- Because the earth turns daily on an axis that is tilted relative to the plane of the earth's yearly orbit around the sun, sunlight falls more intensely on different parts of the earth during the year. The difference in heating of the earth's surface produces the planet's seasons.
- The moon's orbit around the earth once in about 28 days changes what part of the moon is lighted by the sun and how much of that part can be seen from the earth—the phases of the moon.

***Figure 3. SFAA* learning goal concerning explanations of celestial phenomena and the corresponding benchmarks.**

The cycling of water in and out of the atmosphere plays an important part in determining climatic patterns - evaporating from the surface, rising and cooling, condensing into clouds and then into snow or rain, and falling again to the surface where it collects in rivers, lakes, and porous layers of rock (*Science for All Americans*, p. 39).

By the end of the 2nd grade, students should know that:

- Water can be a liquid or a solid and can be made to go back and forth from one form to the other. If water is turned into ice and then the ice is allowed to melt, the amount of water is the same as it was before freezing.
- Water left in an open container disappears, but water in a closed container does not disappear.

By the end of the 5th grade, students should know that:

- Air is a substance that surrounds us, takes up space, and whose movement we feel as wind.
- When liquid water disappears, it turns into a gas (vapor) in the air and can reappear as a liquid when cooled, or as a solid if cooled below the freezing point of water.
- Clouds, like fog and "steam" from a kettle, are made of tiny droplets of water.
- No matter how parts of an object are assembled, the weight of the whole object made is always the same as the sum of the parts; and when a thing is broken into parts, the parts have the same total weight as the original thing.

By the end of the 8th grade, students should know that:

- Heat can be transferred through materials by the collisions of atoms or across space by radiation. If the material is fluid, currents will be set up in it that aid the transfer of heat.
- No matter how substances within a closed system interact with one another, or how they combine or break apart, the total weight of the system remains the same.
- Water evaporates from the surface of the earth, rises and cools, condenses into rain or snow, and falls again to the surface. The water falling on land collects in rivers and lakes, soil, and porous layers of rock, and much of it flows back into the ocean.

By the end of the 12th grade, students should know that:

- Life is adapted to conditions on the earth, including the force of gravity that enables the planet to retain an adequate atmosphere, and an intensity of radiation from the sun that allows water to cycle between liquid and vapor.
- Transfer of heat energy at the boundaries between the atmosphere, the land masses, and the ocean, results in layers of different temperatures and densities in both the ocean

> and atmosphere. The action of gravitational force on regions of different densities causes them to rise or fall -- and such circulation, influenced by the rotation of the earth, produces winds and ocean currents.

***Figure 4. SFAA* learning goal concerning the water cycle and the corresponding benchmarks.**