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Why Unguided Learning Does Not Work:
An Analysis of the Failure of Discovery Learning, Problem-Based Learning, Experiential Learning and Inquiry-Based Learning

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Abstract

Drawing on examples from science and medical education, evidence and explanations for the superiority of guided instruction are explained in the context of expert-novice differences, cognitive load and cognitive architecture. While unguided or minimally-guided learning approaches are very popular and intuitively appealing, the point is made that evidence from empirical studies over the past half century consistently indicates that they are less effective and less efficient than learning approaches that place a strong effort on guidance of the student learning process. Only when learners have sufficient high prior knowledge that provides ‘internal’ guidance does the advantage of guidance begin to reduce. Recent developments in instructional research and instructional design models that support guided learning are briefly described.

Why Unguided Learning Does Not Work: An Analysis of the Failure of Discovery Learning, Problem-Based Learning, Experiential Learning and Inquiry-Based Learning

Disputes about the impact of instructional guidance during learning have been ongoing for at least the past half century (Craig, 1956; Ausubel, 1964; Shulman & Keisler, 1966; Mayer, 2004). On one side in this argument are those who advocate the hypothesis that people learn best in an unguided or minimally guided environment where they are primarily asked to mimic the problem-solving activities of experts and/or learn and discover collaboratively with others. This approach has been called by various names including discovery learning (Bruner, 1961; Anthony, 1973); problem-based learning (Barrows & Tamblyn, 1980; Schmidt, 1983), inquiry learning (Papert, 1980; Rutherford, 1964), experiential learning (Boud, Keogh, & Walker, 1985; Kolb & Fry, 1975) and constructivist learning (Jonassen, 1991; Steffe & Gale, 1995). Examples of applications of these differently named but essentially identical approaches include science instruction where students are placed in inquiry learning contexts and asked to discover the fundamental and well-known principles of science by modeling the investigatory activities of professional researchers; medical students in problem-based learning courses who are required to discover medical solutions for common patient problems using problem-solving techniques; and people at work who are asked to collaborate to construct a strategy for achieving a goal.

The main assumption underlying these learning programs is that they challenge students to solve ‘authentic’ problems or learn complex knowledge in information rich settings based on the assumption that having learners construct their own solutions leads to the most effective learning experience. Minimal guidance is offered in the form of task-relevant information that is available if learners choose to use it. Advocates of this approach imply that instructional guidance that provides or embeds learning strategies in instruction interferes with the natural processes by which learners draw on their unique, prior experience and learning styles to construct new, situated knowledge that will achieve their goals. This constructivist argument has attracted a significant following.

The goal of this article is to argue that the past half century of research on this issue has provided overwhelming and unambiguous evidence that unguided or minimally guided learning is significantly less effective and efficient than guidance that is specifically designed to support the cognitive processing necessary for learning. Not only is minimally-guided learning ineffective for most learners, it may even be harmful for some (Clark, 1989). Even in cases where instruction is being provided to learners who have considerable prior learning or expertise in a topic, unguided learning is often no more effective than guided learning. The best evidence developed over the past half century supports the view that minimally-guided learning does not enhance student achievement any more than throwing a non-swimmer out of a boat in the middle of a deep lake supports learning to swim.

Our Goal. In our discussion, we will point to evidence that 50 years of well-designed experiments comparing unguided and weakly guided instruction with strongly guided instruction have demonstrated the unambiguous and overwhelming learning benefit of specific types of strong instructional guidance. We will also provide evidence that while all forms of guidance are not equal and that some forms can prevent learning, in general, guidance tailored by our knowledge of cognitive architecture results in either significantly more learning and transfer or, in the case of advanced experts, is frequently as effective as unguided learning. We will also suggest that this evidence is largely ignored by advocates of unguided instruction. In an attempt to explain why unguided instruction is so attractive to advocates, we examine the 'post Sputnik' curriculum reform movements and current evidence from research on self-reflection. We then turn to a description of new instructional design models for guided learning and explain their more positive impact by drawing on current theory and research on the development of expertise and our current understanding of cognitive architecture.

Research Comparing Guided and Unguided Instruction

A number of reviews of empirical studies have established a solid research-based case against the use of unguided learning. While an extensive review of those studies is outside the scope of this article, Mayer (2004) has recently reviewed evidence from studies conducted from 1950 to the late 1980's comparing 'pure discovery learning', defined as unguided, problem based instruction with guided forms of instruction. He suggests that in each decade since the mid 1950's, when empirical studies provided solid evidence that the then currently popular unguided approach did not work, a similar approach popped up under a different name with the cycle then repeating itself. Each new set of advocates for unguided approaches seemed either unaware or uninterested in previous evidence that unguided approaches had not been validated. This pattern produced discovery learning which gave way to experiential learning which gave way to problem-based and inquiry learning which now gives way to constructivist learning. Mayer concluded that "The debate about discovery has been replayed many times in education but each time, the evidence has favored a guided approach to learning." (2004, p. 18).

Current Research. More recent evidence from well-designed, controlled experimental studies continues to support direct instructional guidance rather than unguided learning (e.g. see Moreno, 2004; Tuovinen & Sweller, 1999). For example, Hardiman, Pollatsek, and Weil (1986) and Brown and Campione (1994) noted that when students learn science in classrooms with pure-discovery methods and minimal feedback, they often become lost, frustrated, and their confusion can lead to misconceptions. Others (e.g., Carlson, Lundy, & Schneider, 1992; Schauble, 1990) found that since false starts are common in such learning situations, unguided discovery is most often inefficient.

Moreno (2004) concludes that there is a growing body of research showing that students learn more deeply from strongly guided learning than from discovery. Similar conclusions have been reported by Chall (2000); McKeough, Lupart, and Marini (1995); Schauble, (1990); and Singley & Anderson, (1989).

Cognitive Load: Sweller and others (Sweller, 1999; Paas, Renkl, & Sweller, 2003; 2004; Winn, 2003; Mayer, 2001) note that despite the alleged advantages of unguided environments to help students to derive meaning from learning materials, cognitive load theory suggests that the free exploration of a highly complex environment may generate a heavy working memory load that is detrimental to learning. This suggestion is particularly important in the case of novice learners, who lack proper schemas to integrate the new information with their prior knowledge. Tuovinen and Sweller, (1999) have shown that exploration practice (a discovery technique) caused a much larger cognitive load and led to poorer learning than worked-examples practice. The more knowledgeable learners did not experience a negative effect and benefited equally from both types of treatments. Mayer (2001) describes an extended series of experiments in multi-media instruction that he and his colleagues have designed drawing on Sweller's (1988, 1999) cognitive load theory and other cognitively-based theoretical sources. In all of the many studies he reports, guided instruction not only produces more immediate recall of facts than unguided approaches, but also longer term transfer and problem solving skills. His *seven principles of multimedia design* are examples of the practical benefits of systematic research on this issue. It is instructive that Mayer's work highlights a number of areas where attempts to design media-based instruction that is entertaining and to learners actually decreased their learning, most likely due to cognitive overload (Mayer, 2002).

Worked Examples

One example of strongly guided instruction based on cognitive load theory can be found in the worked example effect (see Sweller, 1999; Sweller, van Merrienboer & Paas, 1998, for reviews) which has been replicated a number of times. It occurs when learners solving problems learn less than learners studying the same problems with solutions, i.e. studying worked examples. For novices, studying worked examples seems invariably superior to discovering or constructing a solution to a problem. Problem solving only becomes relatively effective when learners are sufficiently experienced so that studying a worked example is, for them, a redundant activity that increases working memory load compared to generating a known solution (Kalyuga, Chandler, Tuovinen, & Sweller, 2001). In many instances, more experienced learners benefit equally from minimal and strong guidance instruction (e.g. Touvinen & Sweller, 1999).

Process Worksheets

Authentic, complex learning tasks often require problem solving and reasoning skills. A second way of guiding instruction is the use of process worksheets. Process worksheets (van Merriënboer, 1997) provide a description of the phases one should go through when solving the problem as well as hints or rules-of-thumb that may help to successfully complete each phase. In this they provide a systematic approach to problem solving for the whole learning task. Students can consult the process worksheet while they are working on the learning task(s) and they may use it to note down intermediate results of the problem solving process.

Nadolski, Kirschner and van Merriënboer (in press), for example, studied the effects of process worksheets with Law students and found that the availability of a process worksheet had positive effects on learning task performance, indicated by a higher coherence and more accurate content of the legal case being developed..

Research on Educational Models Favoring Unguided Learning in Various Settings

In the 1920's and 30's, the educational philosopher John Dewey pointed out that the authoritarian, strict, pre-ordained knowledge approach of traditional education at that time was too concerned with delivering knowledge, and not enough with understanding students' actual experiences. His best expression of these ideas was described in his *Experience and Education* (Dewey, 1938). Dewey became the philosophical parent of experiential education, or as it was then referred to, progressive education. Yet he was critical of completely 'free, student-driven' education because, as he explained, students often don't know how to structure their learning experiences for maximum benefit. A key element of Dewey's approach was the suggestion that a learner's present experience is a function of the interaction between their past experiences and the present situation.

Experiential Learning at Work. One implementation of some of Dewey's suggestions can be found in the experiential learning approach suggested by Kolb and Fry (1975). Kolb and colleagues seem to have implemented some of Dewey's original idea and substituted what is more commonly called *concrete experience* or *realistic practice* for Dewey's two features of *experience* (the interaction between prior knowledge and current context). Kolb and Fry (1975) argue that the learning process often begins with a person carrying out a particular action and then seeing or discovering the effect of the action in this situation. The second step is to understand these effects in the particular instance so that if the same action was taken in the same circumstances it would be possible to anticipate what would follow from the action. Using this pattern, the third step would be understanding the general principle under which the particular instance falls. Kolb and Fry also suggested a number of learning styles that they hypothesized would influence the way that students took advantage of experiential situations.

All published attempts to validate experiential learning and Kolb and Fry's learning styles appear to have failed. Even some of the researchers who were advocates of their approach have not been able to muster quantitative evidence that supports the predictive validity of his learning styles or experiential methods (Illif, 1994). Iliff concluded that in an analysis of approximately 50 correlational and empirical studies of Kolb and Fry's learning style, and experiential treatments, the evidence is too weak to support the use of the measures or the methods for training at work.

Medical Problem-Based Learning Research

All in all, a lack of clarity about the difference between learning a discipline and research in the discipline coupled with the priority afforded to unbiased observation in the best inductivist-empiricist tradition has led many educators to advocate the discovery method as the way to teach a discipline (Allen, Barker & Ramsden, 1986; Anthony, 1973; Obioma, 1986). Not only did problem-based learning seem to mesh with ideas in, for example, the philosophy of science, but it also fit well with progressive learner-centered views emphasizing direct experience and individual inquiry. Cawthron and Rowell (1978) stated that it all seemed to fit. The logic of knowledge and the psychology of knowledge coalesced under the umbrella term *discovery*. Why, he asked, should educators look further than the traditional inductivist-empiricist explanation of the process?

In an attempt to rescue medical students from numbing lectures and memory-based recall exams, approximately 60 medical schools in North America have adopted problem-based learning (PBL) in the past two decades. This variant of minimally-guided, constructivist learning, introduced at the McMaster University School of Medicine in 1969, asks medical students to work in groups to diagnose and suggest treatment for common patient symptoms. PBL student groups are supervised by a clinical faculty member who is directed not to solve problems for the students but instead to offer alternatives and suggest sources of information. The best known survey of the comparisons of PBL with conventional medical school instruction was conducted by Albanase and Mitchell (1993). Their meta-analysis of the English language literature of the effectiveness of PBL produced a number of negative findings concerning its impact including lower basic science exam scores, no differences in residency selections and more study hours each day. They also found that while PBL students receive better scores for their clinical performance, they also order significantly more unnecessary tests at a much higher cost per patient with less benefit. There was an indication in their review that increased clinical practice evaluation scores may have been due to the fact the PBL students are required to spend more time in clinical settings. Berkson (1993) also reviewed much of the literature on PBL and arrived at many of the same conclusions as Albanase and Mitchell. She reviewed the problem solving ability of PBL students when compared with conventionally trained students and found no support for any differences and so failed to replicate the clinical advantage found by Albanase and Mitchell. Colliver (2000) reviewed existing studies comparing the effectiveness of problem-based learning (PBL) in medicine to conventional medical school curricula. He concluded that PBL studies show no statistical effect in the performance of medical students on standardized tests or on instructor designed tests during the first two years of medical school. Also important for medical educators has been the constant finding in research summaries that PBL is not more effective but is more costly than traditional instruction. Apparently, the practice of a profession should not be confused with learning to practice the profession.

Guided Versions of Problem-Based Learning

The lack of both learning and cost benefits for PBL has led medical schools such as the University of Calgary in Canada to create guided learning variations of PBL called the Clinical Presentation Model (Papa & Harasym, 1999). This model attempts to overcome the problems associated with unguided PBL by providing clear guidance on 120 integrated, authentic medical scenarios that appear to span the range of issues that general practitioners in medicine must handle. Each of the scenarios was developed using cognitive task analysis (Schraagen, Chipman, & Shalin, 2000) with expert physicians. The result is problem based but student instruction is guided with instructional strategies such as clear learning and performance objectives, direct instruction on the basic science processes involved in each scenario, clear worked examples of diagnostic and treatment paradigms for each scenario based on expert cognitive-task analysis, process worksheets to guide the learner through the solution process, and corrective feedback by expert instructors during problem solving. Preliminary studies indicate that the guided Clinical Presentation Model, when it is fully implemented, may be much more effective than either PBL or the traditional medical school curriculum (Woloschuk, Harasym, Mandin, & Jones, 2000).

The Origins of Constructivism and the Current View of Unguided Instruction

The most recent approach to unguided learning comes from *constructivism* which appears to have been derived from observations that knowledge is constructed by learners and so (a) they need to be taught how to construct by being presented minimal information and (b) learning is idiosyncratic and so a common instructional format is ineffective. Educators who disagree with this approach are sometimes referred to by the derogatory term “instructivists” (e.g., Harrington & Standon, 1999). The constructivist description of learning is accurate but the instructional consequences do not follow. Learners of all ages know how to construct knowledge and there is no evidence that presenting them with partial information enhances their ability to construct a representation more than full information. Quite the reverse is true. Learners must construct a mental representation or schema irrespective of whether they are given complete or partial information. Complete information will result in a more accurate representation that is more easily acquired. Furthermore, the fact that all learners have different experiences and somewhat different knowledge organization does not imply that we do not share similar learning processes. Despite all people having unique organs and body chemistry, it is possible to diagnose and treat illness and foster *wellness*. Similarly, the constructivist observation is not evidence that it is impossible to guide learning for most learners with common instructional methods and strategies. Constructivism is based therefore, on an observation that, while descriptively accurate, does not lead to a prescriptive instructional design theory or to effective pedagogical techniques (Clark & Estes, 1998; 1999, Estes & Clark, 1999; Kirschner, Strijbos, & Martens, 2004).Yet an entire generation of educators, educational researchers and learning materials developers appear to have embraced and tried to implement it.

Epistemological Conflict

Some who have been attracted to constructivism are not necessarily persuaded by empirically-based evidence about effectiveness. A number of constructivist advocates reject science and empirical work altogether under the banner of postmodernism. Postmodernist views of research in the 1970’s (for example, Bronfenbrenner, 1976; Phillips, 1983) suggested that controlled experiments could not capture the complexity of learning in authentic settings and that much empirical work was inappropriate for education. These views apparently resonated with educators who were frustrated with the perceived utility of highly controlled and narrowly framed experiments. The challenges of Bronfenbrenner and others have been questioned by critics such as Cromer (1997), Wilson, (1998) and the National Research Council (Shavelson & Towne, 2002) among others. Winn (2003) makes the point that modern research designs that do not attempt to control complexity can provide rich insights about learning and still meet scientific standards for reliability and validity. Examples of these experimental plans can be found in early versions of time series designs such as those described by Clark & Snow (1975), and in more recent structural equation models (Bentler & Weeks, 1980) that allow researchers to examine the relations between many variables in authentic instructional contexts.

Curriculum Reform in the 1950's

Constructivism, and related unguided approaches, can also be viewed as a culmination of a way of thinking about learning and teaching - at least in the natural sciences - which began in the 1950s with a series of curriculum reform projects such as BSCS (Biological Sciences Curriculum Study), CHEM Study (Chemical Education Material Study) and PSSC (Physical Science Study Committee) in the United States and the Nuffield Science projects in Great Britain (Haber-Schaim, Cross, Dodge, & Watter, 1976; Hurd, 1969; Nuffield, 1966). These curriculum reforms, a reaction to the launching of Sputnik in 1957, signaled the onset of cooperative efforts between specialists in discipline areas and specialists in education to improve teaching. They were designed with new rationales for both education in general and the use of practical experience such as science laboratories in particular and were meant to promote meaningful learning and learning by doing. The question is: Do they work?

Practicing or Learning to Practice a Discipline?

Most curriculum reform has resulted in a major shift of emphasis away from teaching a discipline as a body of knowledge towards an exclusive emphasis on the experience of the processes and procedures of the discipline (Hodson, 1988). This change in focus was coupled by many leading educators and discipline specialists with the assumption that knowledge can best be learned or only learned through experience which is based entirely on the procedures of the discipline. This point of view led to a commitment of educators to extensive practical or project work, the rejection of instruction based on the facts, laws, principles and theories that make up a discipline's content, and the use of discovery and inquiry methods of learning. The addition of extra emphasis on the practical application of inquiry and problem-solving skills seems very positive. Yet we believe it is a fundamental error to assume that the pedagogic content of the learning experience is identical to the methods and processes (i.e., the epistemology) of the discipline being studied and a mistake to assume that instruction should exclusively focus on methods and processes.

Knowing Less after Instruction. Not only do students fail to learn much in unguided contexts, compelling evidence exists to suggest that some students actually know less after unguided experiences than they knew at the start of a lesson. Clark (1989) reviewed approximately 70 aptitude-treatment interaction studies where students who choose or are assigned to unguided contexts receive significantly lower scores on post tests than on pre test measures. The context for the studies reviewed ranged from elementary classrooms to university and work settings and included a variety of problems and tasks. Clark (1982, 1989) calls this knowledge reversal a *mathemathantic* effect which he defined as instructional strategies that kill learning. His review points out that mathemanthic errors appear to happen most frequently to learners who have less prior knowledge and/or general ability who are either assigned or choose unguided versions of courses. Even more distressing is the evidence Clark (1982) presents that when learners are asked to select from a more or less unguided version of the same course, those who choose unguided approaches tend to like the experience even though they learn less from them and/or actually reverse their learning and know less after instruction than when they start. Clark (1982, 1989) also notes that the studies he reviewed also provide evidence for the hypothesis that more advanced students seem not to be harmed by less guided approaches and some seem to benefit from them and that some types of guidance can also harm student learning.

Content Knowledge and Pedagogical Knowledge

Shulman (1986, Shulman & Hutchings, 1999) contributed to our understanding of the reason why less guided approaches fail in his discussion of the integration of content expertise and pedagogical skill. He defined *content knowledge* as "…the amount and organization of the knowledge per se in the mind of the teacher." (Shulman, 1986, p. 9); and *pedagogical content knowledge* as knowledge, "…which goes beyond knowledge of subject matter per se to the dimension of subject knowledge for teaching." (Shulman, 1986, p. 9) He further defined *curricular knowledge* as "…the pharmacopoeia from which the teacher draws those tools of teaching that present or exemplify particular content…" (p. 10). Kirschner (1991, 1992) has also argued that the way an expert works in his/her domain (epistemology) is not equivalent to the way one learns in that area (pedagogy). A similar line of reasoning is followed by Dehoney (1995), who posited that the mental models and strategies of experts have been developed through the slow process of accumulating experience in their domain areas. It is therefore not clear what happens if these models and strategies are imposed on learners. They may interfere in as yet unknown ways with the process of acquiring expertise.

Expert Models and Knowledge Accuracy in Constructivist Educational Settings

One way that the content knowledge of experts who serve as constructivist mentors can interfere with learning has been suggested by studies that emphasize the automated and unconscious nature of expert knowledge. In cognitive apprenticeships, inquiry learning and problem-based settings, the mentor's role is to model and explain her or his own approach to problems together with students. In their studies of cognitive apprenticeships, Radziszewska and Rogoff (1988; 1991) report that successful learning by the student is dependent on accurate, comprehensible explanations of strategies by the mentor and the opportunity to participate in decisions during authentic tasks. In this context, the student is dependent on the accuracy of the experts self-report. However, the accuracy of self-report under many conditions is considered highly suspect (e.g. Schneider & Shiffrin, 1977; Wilson & Nisbett, 1978). Bargh (2000) and others (Glaser, 1985; Ohlsson, 1996) have suggested that the automated nature of expertise may account for the evidence that experts often but unintentionally give incomplete and/or inaccurate descriptions of their own cognitive strategies to novices. Since experts cannot directly inspect their own cognitive processing when it has become automated, the self-report aspects of their cognitive mentoring may account for some of the learning difficulties found in comparison studies.

It must be emphasized that we are not arguing against the importance of content knowledge expertise as an essential base for all pedagogy. Nor are we arguing that practice on authentic problems is harmful. Rather, we are arguing that there is a clear distinction between content-knowledge and pedagogical-knowledge. Having learners attempt to discover knowledge without instructional guidance from content-knowledge experts assumes that content knowledge on the part of instructors is irrelevant because learners can apparently discover the content knowledge themselves. On the other hand, attempts to have experts lacking the pedagogical-knowledge model content-knowledge equally assumes that pedagogical-knowledge is irrelevant since learners can apparently simply copy what experts do. Both content- and pedagogical-knowledge are required and merely because it can be difficult for experts to model their knowledge in a manner that is intelligible to learners does not obviate this need. Rather, it emphasizes the need for subject experts to also have pedagogical expertise so that what learners are required to model is intelligible to them.

Although some may be tempted to feel that the aforementioned distinction between what an expert does, what knowledge the expert draws on to do what she or he does, and the pedagogical principles that are appropriate to learn a discipline all result from common sense, these are distinctions that are generally not recognized in modern education. While no one would consider competing in a Formula 1 auto race to be the proper didactic approach for teaching someone to drive a car, many educators have no qualms about embracing the notion that this same didactic approach of exposing learners to the same situations as experts can be applied to teaching. Most if not all of the major reforms in education in the past 40 years make use of this faulty rationale.

Science Education Example

Many curriculum developers, educational technologists, and educators seem to confuse the teaching of a discipline as inquiry (for example a curriculum emphasis on the research processes within science or psychology) with the teaching of the discipline by inquiry (i.e., using the research process of the discipline to learn). Applied to a discipline such as science, the basis of this confusion may lie in what Hurd (1969) calls the rationale of the scientist. According to this rationale, the teaching of science should reflect the nature of science as it is known to scientists and should embody the specific characteristics of the discipline it represents. All disciplines have a conceptual structure identifying the knowledge of which they are composed as well as particular modes of inquiry; ways of gathering information and processing it into data. The methods are disciplined with *ground rules* governing the processes. The rationale of the scientist holds that a science course "should be a mirror image of a science discipline, with regard to both its conceptual structure and its patterns of inquiry. The theories and methods of modern science should be reflected in the classroom. In teaching a science, classroom operations should be in harmony with its investigatory processes and supportive of the conceptual, the intuitive, and the theoretical structure of its knowledge" (Hurd, 1969, p. 16). This rationale assumes "that the attainment of certain attitudes, the fostering of interest in science, the acquisition of laboratory skills, the learning of scientific knowledge, and the understanding of the nature of science were all to be approached through the methodology of science, which was, in general, seen in inductive terms" (Hodson, 1988, p. 22). The major fallacy of this rationale is that it makes no distinction between the behaviors and methods of a researcher who is an expert practicing a profession and those of a student who is essentially a novice.

According to Kyle (1980), scientific inquiry is a systematic and investigative performance ability incorporating unrestrained thinking capabilities after a person has acquired a broad, critical knowledge of the particular subject matter through formal learning processes. It may not be equated with investigative methods of science teaching, self-instructional learning techniques and/or open-ended learning techniques. Educators who equate these are guilty of the improper use of inquiry as a paradigm on which to base a teaching strategy.

Finally, Novak (1988), in noting that the major effort to improve secondary school science education in the 1950s and 1960s fell short of expectations, goes so far as saying that the major obstacle which stood in the way of “revolutionary improvement of science education . . . was the obsolete epistemology that was behind the emphasis on ‘inquiry’ oriented science” (pp. 79-80).

The Distinction between “Learning” and “Working” in a Science-based Discipline

The origin of this insistence that curricula should reflect the activities of researchers (or other professional fields) may be the failure to distinguish between teaching and learning a discipline on the one hand and practicing the discipline on the other. The aims of teaching and learning need not necessarily coincide with those of practice. Many current educators and curriculum developers operate in the belief that the way a discipline is practiced is also the best way to teach and learn. The philosophy of a discipline is a necessary, although not a sufficient condition for theories of teaching. For example, in science, “It is naive to assume that a theory of education can be extracted directly from a philosophy of science. These two phenomena belong to different domains; albeit overlapping domains in some aspect” (Swift, 1982, p. 39). Hodson (1988), in alluding to what he calls the mythology of the science teaching profession, postulates that perhaps it is because experiments are widely used in science that science teachers are conditioned to regard them as a necessary and integral part of science education. They confuse doing science with learning science and learning about science. As a consequence of this confusion, educators also confuse projects and practical work and their purpose in education with projects or experiments and their purpose during research. The mistake of some educators lies in overlooking that students do not practice science, mathematics or historical research et cetera., but are learning about the discipline and/or learning to practice the discipline and that it is the teacher's job to teach the discipline, teach about the discipline and teach how to engage in the discipline (Hodson, 1985). None of these activities necessarily involve the specialized activity of conducting research.

Teaching Science by Doing Science

Woolnough and Allsop (1985) summed up this point of view by stating that in teaching science, educators should be concerned with introducing students to a body of knowledge and familiarizing them with the way a problem solving scientist works. For example, the charge of an electron was painstakingly determined by Millikan in his famous oil drop experiment. The knowledge is the charge of the electron, the set-up of the experiment, and even the thinking that brought him to act in this way. The way this scientist worked is reflected in the many trials it took to reach an accurate result. The procedure can better be taught than discovered. This conclusion does not mean that the practical should be avoided. The learner who now knows and understands the procedures used could/should experience how inexact such apparatus was and how large experimental error can be, but this *knowledge* has more to do with what it feels like (affective aspects of being a scientist) than cognitive ones. In other words, this kind of laboratory work can play a role in the development of attitudes toward science. Science should be taught as “inquiry as it appears in the scientific enterprise”, i.e., inquiry as content, instead of “using the method of scientific inquiry to learn some science”, i.e., inquiry as technique, (Rutherford, 1964, in SciMath^{MN}, 1998). The essential point here, seemingly trivial yet often ignored, is again that there is a world of difference between the scientist and the student. Anderson (1976) defined the relationship between the scientist, sciencing (also called scientific inquiry) and science as follows:

– A *scientist* is a person with a social role, committed to investigation, accumulating knowledge and possessing not only a great deal of knowledge about a body of knowledge, but also a keen sense of prediction about natural phenomena.
– *Sciencing* is the application of inquiry methods, both physical and intellectual, to probe the enigmatic properties of nature.
– *Science* is a body of knowledge and methodologies that stand as the cumulative product of the scientist's use of scientific processes. It is also a way of thought and a system of methodologies that are given to the task of interpreting natural phenomena. As a school subject it is unique in that students can learn to apply systematic thought to the analysis of measurable natural phenomena as presented in immediate sensory experience.

A student, on the other hand, is still learning about the subject area in question and as such does not possess the theoretical sophistication nor the wealth of experience of the researcher. Ausubel (1964) had great problems with this failure to differentiate between, for example the scientist and the student. According to him, scientists are engaged in a full-time search for new, general or applied principles in a field, whereas students are engaged in learning the basic subject matter of a field which scientists learned in their student days plus the way in which scientists practice. If students are ever to discover scientifically, then they must first learn both the content as well as how to discover! The student "cannot learn adequately by pretending [to be] a junior scientist" (p. 298). Kirschner (1991, 1992) too has argued that the way an expert works in his/her domain (epistemology) is not equivalent to the way one learns in that area (pedagogy).

SciMathMN (1998) in its Framework for Science discusses best practice in science and math education. In this discussion it posits: "Scientific inquiry, [this] dialogue between the natural world and the inquirer, must take into account the differences between students and scientists. Scientists differ in what they know as well as in their laboratory and field skills (students are far less persistent, also!). Scientific inquiries are forms of argument and the emphasis should be on interpretation and the generation of new questions. Students are learning to participate in the scientific community as apprentices" (p. 2.29).

Empirical Evidence about Science Learning from Unguided Sciencing

A series of reviews by the U. S. National Academy of Sciences have recently described the results of experiments that provide evidence for the negative consequences of unguided science instruction at all age levels and across a variety of science and math content. McCray, de Haan, and Schuck (2003) review studies and practical experience in the education of college undergraduates in engineering, technology, science and mathematics. Gollub, Berthanthal, Labov, and Curtis (2003) have reviewed studies and experience teaching science and mathematics in High School. Kilpatrick and Swafford (2002) have reported studies and made suggestions for elementary and middle school teaching of mathematics. Each of these and other publications by the U.S. National Academy of Sciences amply document the lack of evidence for unguided, sciencing approaches and the benefits of more strongly guided instruction. Most provide a set of instructional principles for educators that are based on solid research. These reports were prepared, in part, because of the poor state of science and mathematics education in the United States.

There are many techniques available for the teaching and learning of the substantive structure of a domain of knowledge. These techniques may be passive or active, may be based on reception learning or discovery learning, may be rote or meaningful, may be delivered in oral, written, or electronic formats, may make use of age old media (chalk-and-talk) or be at the cutting edge of modern media technologies (interactive multimedia, tele-education, intelligent tutoring technologies). These techniques can be very sensitive to the needs of individual learners, can cater to their preferences, their ages, cultures and social backgrounds or they can be very rigid, tailored to suit large, heterogeneous groups of learners and be mass produced for use in a mass market.

Instructional Design for Guiding the Learning of Complex Knowledge

There are a variety of research-based approaches to developing new instructional designs that are capable of supporting the learning of complex knowledge. Examples include new design theories for teaching problem solving (Reigeluth, 1999a, 1999b), for technical training (Sweller, 1999), arguments for new context and technology-based design (e.g. Driscoll & Dick, 1999), analyses of the cognitive basis for farther transfer of learning and suggestions for ways to design learning experiences to facilitate transfer

(Clark & Blake, 1997), two decades of systematic design research and development on complex learning issues by John Anderson (1983, 1993, 1996; Anderson & Lebiere, 1998), innovative work on *first principles of instruction* by designer-researcher David Merrill (2002a), recent summaries of pedagogical research on problem solving (e.g. Mayer, 2003), the U.S. National Research Council's summary of pedagogical research (Bransford, Brown & Cocking, 2000) and a new comprehensive design model proposed by van Merriënboer (1997; van Merriënboer, Clark & de Croock, 2002). These welcome discussions have at least one important goal in common—the gradual evolution of instructional design models that benefit from cognitive theories of learning to support complex learning through systematically guided instruction. Merrill (2002a) has provided a very useful qualitative summary of the key features of a number of these new design models and has translated them into a set of *first principles of design*.

Merrill's Pebble in a Pond Model of Guided Instructional Design

Merrill (2002a) assembled some of the most popular guided instruction models in use today and looked for the key features of each model. He refers to the resulting framework as *first principles of instruction* and suggests that most of the most effective guided instructional models shared five key phases or elements: (1) A real world problem that represents the kinds of problems we want learners to be able to solve (2) activation of prior experience, (3) demonstration of skills through a worked example or simulation, (4) application of skills in practice, and (5) planned integration of these skills into real-world activities. Merrill (2002b) tested his model in a lesson on how to use excel spreadsheets. Three conditions were compared: 1) An authentic problem where learners are asked to construct an excel spreadsheet with no instructional guidance; 2) Standard training provided with the Microsoft Excel® program, a minimal guidance condition; and 3) Strongly guided instruction based on the first principles described above. Subjects were 128 college students with no previous Excel® experience.

****INSERT TABLE 1 ABOUT HERE****

All learning and time comparisons in Merrill's study were statistically significant from each other (see Table 1). In the condition that most closely approximates unguided authentic problem solving, most students did not finish the development of the spreadsheet in the one hour allotted for solving the problem.

Whatever their similarities or differences, what binds all of the strongly guided techniques for the design and delivery of instruction is that their goal is the conveyance of the content and structure (the facts, rules, principles, concepts and so forth) of a knowledge domain to support the effective application of knowledge by learners. The instructional methods they select for guiding learning are drawn from our current understanding of cognitive architecture and the way it functions to support complex learning. Investigative, constructivist, minimally-guided techniques do not lend themselves to this aim.

The Evolution and Consequence of Cognitive Architecture for Unguided Learning

There are other reasons why the procedures of a discipline are inappropriate as the only strategy for teaching. STEM disciplines (science, technology, engineering and mathematics) have developed only recently in human history, and for a very good reason: While human cognitive architecture permits the accumulation of scientific knowledge, it does not do so quickly, easily or naturally. Humanity required uncounted millennia before appreciable knowledge of science, usually gained through *real* inquiry, emerged.

Based on this slow development, it can be argued that our cognitive processes do not lend themselves to the inquiry-based methods essential for the discovery of new knowledge. In this section we consider some structures that constitute human cognitive architecture, how they function and why they evolved. These structures have implications for the processes involved in inquiry-based learning.

Human Cognitive Architecture

Most modern treatments of human cognitive architecture use the Atkinson and Shiffrin (1968) sensory memory/working memory/long-term memory model as their base. Sensory memory is not relevant to the current discussion and so will not be considered further. The intricate relations between working and long-term memory in conjunction with the functions of learning are of critical importance to the argument.

Our understanding of the role of long-term memory in human cognition has altered dramatically over the last few decades. It is no longer seen as a passive repository of discrete, isolated fragments of information that permit us to repeat what we have learned. Nor is it seen only as a component of human cognitive architecture that has merely peripheral influence on complex cognitive processes such as thinking and problem solving. Rather, long-term memory is now viewed as the central, dominant structure of human cognition. Everything we see, hear and think about is critically dependent on and influenced by, long-term memory.

De Groot's (1965) followed by Chase and Simon's (1973) work on chess can probably be marked as the major influences on the field's re-conceptualization of the role of long-term memory. The finding that expert chess players are far better able than novices to reproduce briefly seen board configurations taken from real games, but do not differ in reproducing random board configurations, has been replicated in a variety of other areas (e.g. Egan & Schwartz, 1979; Jeffries, Turner, Polson, & Atwood, 1981; Sweller & Cooper, 1985). These results suggest that expert problem solvers derive their skill from drawing on the extensive experience stored in their long term memory and quickly select and apply the best procedures for solving problems. The fact that these differences can be used to fully explain problem solving skill emphasizes the importance of long-term memory to cognition. We are skilful in an area because our long-term memory contains huge amounts of information concerning the area. That information permits us to quickly recognize the characteristics of a situation and indicates to us, sometimes unconsciously, what to do and when to do it. In other words, information causes change. To cite/paraphrase Claude Shannon: “Information causes change. If it doesn’t, it’s not information” (in Burke, 1999; Shannon, 1948). Without our huge store of information in long-term memory, we would be largely incapable of everything from simple acts such as crossing a street (our information in long-term memory informs us how to avoid speeding traffic, a skill many other animals are unable to store in their long-term memories) to complex activities such as playing chess or solving mathematical problems. Thus, our long-term memory incorporates a massive knowledge base that is central to all of our cognitively based activities.

Working Memory Characteristics and Functions

Working memory can be equated with consciousness. We are only conscious of the information currently being processed in working memory and are oblivious both of the far larger amount of information stored in long-term memory and not currently brought into working memory as well as to all information available from our environment that is not currently being perceived and processed. The major function of working memory is to process information.

Working memory has two well-known characteristics: it is very limited both in duration and capacity. We have known at least since Peterson and Peterson (1959) that almost all information stored in working memory and not rehearsed is lost within 30 sec and have known at least since Miller (1956) that the capacity of working memory is limited to only a very small number of elements. That number is about 7 according to Miller, but may be as low as 4 plus or minus 1 (e.g., see Cowan, 2001). Furthermore, when processing rather than merely storing information, the number of items that can be processed may only be 2 or 3, depending on the nature of the processing required.

The interactions between working memory and long-term memory may be even more important than the processing limitations (Sweller, 2003). The limitations of working memory only apply to new, yet to be learned information that has not been stored in long-term memory. New information such as new combinations of numbers or letters can only be stored for brief periods with severe limitations on the amount of such information that can be dealt with. In contrast, when dealing with previously learned information stored in long-term memory, these limitations disappear. In the sense that information can be brought back from long-term memory to working memory over indefinite periods of time, the temporal limits of working memory become irrelevant. Similarly, there are no known limits to the amount of such information that can be brought into working memory from long-term memory. Indeed, the altered characteristics of working memory when processing familiar as opposed to unfamiliar material has induced Ericsson and Kintsch (1995) to propose a separate structure, long-term working memory, to deal with well-learned and automated information.

Implications of Human Cognitive Architecture for Constructivist Learning

These memory structures and their relations have implications for instructional design (e.g., Sweller, 1999; Sweller, van Merrienboer & Paas, 1998), especially inquiry-based instruction. By definition, inquiry-based instruction requires search. All problem-based search makes heavy working-memory demands (Sweller, 1988). Furthermore, that working memory load does not contribute to the accumulation of knowledge in long-term memory because while working memory is being used to search for problem solutions, it is not being used to learn. Indeed, it is possible to search for extended periods of time with quite minimal alterations to long-term memory. As indicated previously, the goal of education is not searching or discovering information. The goal is to find it and store it in long-term memory. If there are no alterations to long-term memory, nothing has been learned.

Theoretical work on unguided learning almost never mentions human cognitive architecture. The consequences of search for problem solutions on a limited working memory or the mechanisms by which unguided or minimally-guided learning might facilitate change in long-term memory are routinely ignored. The result is a set of differently named but similar minimally guided learning approaches that are disconnected from much that we know of human cognition. Even worse, unguided learning is a procedure that stands in direct contradiction to the implications that flow from our knowledge of human cognitive architecture. That situation was excusable when Bruner (1961) proposed discovery learning as an instructional tool because the structures and relations that constitute human cognitive architecture had not yet been mapped. We now are in a quite different environment. The structures, functions and characteristics of working and long-term memory, the relations between them, and their consequences for learning and problem solving are clearer now and should be central to the design of effective, guided instruction.

The Evolution of Human Cognitive Architecture

Having established some of the characteristics of human cognitive architecture, it is appropriate to ask why cognition has those characteristics. Specifically, we can ask why human cognition evolved with its particular structures and functions rather than with alternative characteristics (Sweller, 2003; 2004). We argue that the logic that underlies human cognition is identical to the logic that underlies evolution by natural selection and that this logic in turn determines which pedagogical devices are likely to be effective.

There are several basic points of analogy between biological evolution and human cognition.

- Both biological evolution and human cognition include an information store sufficiently massive to permit the system to behave appropriately in a complex environment. Biological evolution relies on a massive genome while human cognition equally relies on a massive long-term memory. Both are central to the manner in which the systems function.
- In order to function flexibly and adaptively, the information stores used by biological evolution and human cognition must be capable of being altered in order to increase coordination with the environment. There is no ultimate, logical driver of alterations to the genetic store other than random alterations with each

alteration tested for effectiveness and either retained or lost over subsequent generations. Similarly, while most human learning that occurs requires the assimilation of information obtained from others, if such knowledge is unavailable, learning ONLY can occur by the random generation of problem solving moves which then are tested for effectiveness and retained if useful. It may be argued that such random generation eliminates purpose and direction. In fact, even where random generation occurs, it will be normally associated with knowledge to provide purpose and direction. In other words, which random moves are proposed will depend on a knowledge base just as which genetic mutations occur will depend on the current genetic base.

– Mechanisms are required to ensure that only a limited number of random variations to the store are considered. Large variations to a genome are virtually never adaptive and as a consequence, genomes alter very slowly (Dawkins, 1986; Poon & Otto, 2000; Simpson, 1949). As a matter of fact, humans share over 99% of their DNA with chimpanzees despite last having had a common ancestor millions of years ago. Similarly, large alterations to a working memory store are unlikely to be adaptive and we have a limited working memory to ensure that only small alterations occur.

These points of analogy suggest that biological evolution and human cognition share a common, natural, information processing system that underlies both processes. This is not surprising since human cognitive architecture is itself a result of this same biological evolution. If so, that commonality is likely to have instructional implications. It was suggested previously that knowledge of human cognitive architecture was essential to instructional design including procedures such as unguided learning. If the analogy proposed here is valid, then we may be in a position to use knowledge of biological evolution to throw light on learning and creativity in natural, information processing systems. That knowledge could be very useful because much more is known of the mechanisms of evolution by natural selection than of human cognitive architecture. Information concerning evolution could address issues in cognition that are relevant to the viability of unguided learning and its related pedagogies.

Knowledge, Learning and Creativity in Natural, Information Processing Systems

In one sense, biological systems are knowledge-based systems. Huge quantities of ‘knowledge’ are incorporated in a genome. An individual is adapted to its environment not because it has ‘discovered’ the right set of genes for its circumstances but because it has obtained the right set of genes from its ancestors. Similarly, an individual should obtain appropriate knowledge from his or her teachers, not attempt to discover the information. In another sense, biological systems are ‘learning’ systems. Through evolution, all of the knowledge incorporated in a genome has been ‘learned’ and that learned information allows a species to survive in a particular environment. In a third sense, biological systems are ‘creative’. Evolution has created the biological world and indeed, has been far more creative than the creativity exhibited by humans. We are not only unable to duplicate most biological systems, we are not able to understand many such systems with entire industries created in an attempt to throw light on biological processes.

The logic of the procedures we use to discover new knowledge is identical to that used by evolving species. We propose new possibilities and test them for effectiveness.

Researchers have no choice but to use this technique because there is no one to provide the appropriate knowledge. There is no reason to use such a slow, ineffective procedure when teaching students because when teaching, there is someone to provide the knowledge - a teacher or some other guided instructional system.

If creativity is common to both evolution by natural selection and human cognition, it is appropriate to ask the role that unguided, inquiry learning might have in encouraging creativity. We can begin by asking how one might increase the ability of evolution to create new functions, procedures and structures. The obvious answer is there is no way. We can use knowledge to alter a genome and the genetic ‘knowledge’ of individuals can be and is transmitted to other individuals. Similarly, there is no way to increase the creativity of human beings. We can and do transmit the knowledge of one individual to other individuals, but if an individual is be creative, the only way is to make small, random alterations to that knowledge and test the alterations for effectiveness. Furthermore, this mechanism is identical to the one used by evolution by natural selection. It is difficult to see how unguided, inquiry based learning can have any role in this procedure other than to slow down knowledge acquisition.

Conclusions

Despite a half century of advocacy associated with unguided, constructivist learning, there is no body of research supporting the technique. In so far as there is any evidence from controlled studies, it almost uniformly supports direct, strong instructional guidance rather than constructivist-based minimally-guided learning. Even for students with considerable prior knowledge, strongly guided learning can be equally effective as unguided approaches. Not only is unguided instruction normally less effective, there is evidence that it may have negative results when students acquire misconceptions or incomplete knowledge. While the reasons for the ongoing popularity of a failed approach are unclear, the origins of the support for unguided learning in science education and medical education might be found in the post-Sputnik science curriculum reforms. At that time, educators seemed to shift away from teaching a discipline as a body of knowledge towards the assumption that knowledge can best or only be learned through experience which is based only on the procedures of the discipline. This point of view appears to have led to unguided practical or project work and the rejection of instruction based on the facts, laws, principles and theories that make up a discipline's content. The emphasis on the practical application seems very positive. Yet we believe it is a fundamental error to assume that the pedagogic content of the learning experience is identical to the methods and processes (i.e., the epistemology) of the discipline being studied and a mistake to assume that instruction should exclusively focus on methods and processes. We regret that current constructivist views have become ideological and often epistemologically opposed to the presentation and explanation of knowledge. We share the puzzlement of Handelsman et al. (2004) who, when discussing science education, ask: "… why do outstanding scientists who demand rigorous proof for scientific assertions in their research continue to use and, indeed defend on the bias of intuition alone, teaching methods that are not the most effective?" (p. 521). We agree with Mayer's (2004) recommendation that we "…move educational reform efforts from the fuzzy and unproductive world of ideology—which sometimes hides under the various banners of constructivism—to the sharp and productive world of theory-based research on how people learn." (p. 18).

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Table 1

Merrill's study of Unguided, Minimally-Guided and Strongly Guided training to use excel spreadsheets

	Percent Learned	Learned Time
Unguided	34%	60 min+*
Minimally Guided	68%	49 min
Strongly Guided	89%	29 min

* Most "unguided" students did not complete the learning tasks

All cells in each column are significantly different from each other at the .001 level