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In the present paper we seek to provide further support for the four phases describing the Process of Science by considering the parallels between biological evolution and the development of scientific knowledge in the individual as well as in the scientific community. Based on the evolutionary model and the four phases, misconceptions regarding the Process of Science are discussed and implications for teaching and learning are presented.

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Teaching, Learning and the Process of Science:
Some Misconceptions

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Introduction

Young and Mermelstein (1992) extended Popper's Falsification Methodology, which focused on the "external" - testable hypotheses performed by the members of the scientific community, to include the "internal" - the psychological processes of the individual. Young and Mermelstein (1992) described the Process of Science as a coordination of the external and the internal in four phases. They are as follows: Phase I - Conjectures and the exploration of error (mistakes) by the individual investigator. Phase II - Emergence of deductions and partial understanding from the investigator's conjectures and mistakes; hypotheses are generated. Phase III - Attempts at falsification of these hypotheses by the investigator and the scientific community are initiated. Phase IV - Implications are made from these hypotheses which are not conceivable from rival falsified hypotheses.

In the present paper we seek to provide further support for the four phases describing the Process of Science by considering the parallels between biological evolution and the development of scientific knowledge in the individual as well as in the scientific community. Based on the evolutionary model and the four phases, misconceptions regarding the Process of Science are discussed and implications for teaching and learning are presented.

Evolutionary Model

Piaget (1971), Campbell (1971), Kuhn (1970), and Popper (1961) have suggested parallels between biological evolution and the development of scientific thought. Campbell (1971) in describing biological process points to the suggestion that mutation can be caused by either external or internal factors. The fundamental biological assumption that a gene can mutate without environmental pressure suggests further parallels with the Process of Science particularly phase I and phase II.

Popper's (1961) model serves as a starting point for demonstrating parallels between biological evolution and the Process of Science. His model is described as follows:

P1---->TS---->EE---->P2 (Process of Science)
S1---->MU---->NS---->S2 (Biological Evolution)

For Popper P1 represents the problem identified, TS the tentative solutions or hypotheses, EE error elimination or Falsification and P2 represents the new problem which emerges as a consequence of this Falsification. Falsification is for Popper the Process of Science. It is the methodology of Science which is external and applicable to the scientific community as a whole.

S1, a particular species, according to Popper, is analogous to P1; MU, the mutations are similar to TS. NS, natural selection, indicates which of the mutations are eliminated and which survive and thus mirror EE in the Process of Science. S2, the new species which survives, is akin to P2.

Like the science model, the biological model is external. Natural selection, error elimination ,occurs in the external environment. Popper's model conforms to Phase III and Phase lV of the Young and Mermelstein (1992) model. It will be demonstrated that Popper's parallels between biological evolution and the Process of Science with appropriate modifications are applicable to Phase I and Phase II of the Young-Mermelstein model and indeed provide additional evidence as to the validity of the four phases. Popper's model may be described as a community model.

That is, P1 is a problem identified as such by the scientific community as a whole. Similarly S1 refers to a community of individuals and not any one given individual. What is required is a model in which the individual scientist and the individual gene are included. Campbell (1960) in his work on psychology of knowledge processes points out that variation (mutation) and selection can come out from both external and internal processes.

The model of the individual may be described as follows:

SlPl----TS---->EE----P1 (Science-Individual)
GS1----MU----NS----S1 (Bio. Evolution)

S1P1 refers to an individual scientist sensing a problem but unable to identify the problem; TS the tentative solutions toward identifying what P1 is; EE the elimination of the individual scientist's mistakes and P1 the identification of the problem.

GS1 refers to the gene of the Species S1; MU the mutation that the gene must undergo, and NS the internal selection (i.e. a permutation of molecules which chemistry allows) then permits S1 to express itself.

As in Popper's model S1P1 is analogous to GS1, TS is similar to MU, EE is akin to NS and P1 is analogous to S1. In this model, we describe an Internal Falsification Process for Science and an Internal Selection process for biological evolution.

The Science-Individual model describes an "Internal" Falsification process that occurs in the mind of the individual scientist. As we have mentioned in our earlier paper, this process is characterised by the individual scientist's need to identify the problem, his quest for understanding which propels him to make mistakes and explore them. Similarly, the biological evolution gene model has an "Internal" Selection process which generates a particular mutation of a gene and this permits expression of a Species.

The model we propose for describing the Process of Science and biological evolution is an extension of Popper's model. It is the coordination of the Internal and External Falsification (Selection) Process and is described as follows:

Individual   Community
S1P1---->TS---->EE----> P1-:-->P1---->TS----EE---->P2

GS1---->MU---->NS---->S1-:-->S1---->MU---->NS---->S2

As with Popper's model this extended model demonstrates the differences between biological evolution and the Process of Science as well as the similarities. Specifically, whereas the Process of Science is goal directed (EE), biological evolution is random (NS) and thus diversified.

Misconceptions

The parallels between the Process of Science (Phases I-IV) and biological evolution suggest an evolutionary model for the Process of Science. What some may identify as misconceptions, and others as a different point of view regarding the Process of Science will be addressed. Specifically, mistakes and errors, as well as the relationship between the individual scientist and the Process of Science will now be discussed.

That trial and error strictly speaking belong to the scientific community as a whole whereas mistakes belong to the individual scientist derive from personal scientific experience and teaching. What makes mistakes individual is that they are "I" openers; that is they allow the individual to become the foremost interpreter of his own experience. In this sense mistakes are vehicles for discovery. Making mistakes permits one to "SEE" what one does not understand and thus are exploratory in nature. In science the individual who senses a problem but does not know what it is, is propelled into making mistakes. Why? Simply put, it is the individual's quest for understanding the phenomena in front of him. Kenealy (1989) points out that Kepler consciously make public his mistakes and wandering to show how his discoveries were made. He said of his mistakes that ... they are not less admirable than the discoveries themselves... Thus mistakes are attempts at clarification which represent the individual's quest for understanding. These mistakes, this probing, gives birth to new organs of perception from Goethe's point of view (in Zajonc 1992 p.194) and the development of cognitive structures from Piaget's point of view. These organs of cognition are inner lights which illuminate the field of observation and provide the understanding of the phenomena. The individual, it should be pointed out, is not seeking an explanation, but seeks to "frame" phenomenon into some coherent whole. It follows that these organs of cognition are the mechanism for conceptual change of the individual scientist. The individual scientist's psychology of learning is characterised by the freedom to make mistakes, in which attempts at identifying the problem lead to the development of organs of cognition which on the one hand articulate the relationship between the individual scientist and the Process of Science and on the other hand provide the mechanism for conceptual change.

To incorporate the individual scientist's psychology of learning into the Process of Science provides us on the one hand with a mechanism to examine investigator bias and on the other hand requires us to abandon the notion of a scientific methodology which is independent of the investigator. Thus Science's objective is not so much to be free of bias or "error" but to be aware of bias and take it into account in our findings. Of interest is that we do not wish to eliminate bias or "error" but rather be aware of it so that we may explore "error" and achieve new insights into the phenomena we are studying. Recent distinctions between the context of justification and the context of development, however, seems to unwittingly promote a methodology which is independent of the investigator. Duschl, Hamilton, and Grandy (1992) speak of the historical context of development in

contrast to the ahistorical context of justification. They state: "The context of development approach is concerned with the way restructuring of knowledge has taken place and with establishing a basis for understanding the generation of new scientific evidence and the shift in commitment from one theory to another. Thus changes in knowledge, in method, and in aims are equal partners in the restructuring of scientific knowledge."(p.36) The shift in terminology from context of discovery to context of development, we believe,
reflect a shift from a more individual psychology of learning with all its uncertainties as well as concerns for its scientific credibility, to a process which is external (historical) and hence observable and subject to "test" in some sense. In other words, the individual investigator is silenced but he nevertheless, casts a shadow over the field of observation.

Not only does the notion of investigator bias flow from
the notion of developed organs of cognition, but indeed the notion of conceptual change does also. Conceptual change from this point of view suggests an individual psychology of learning with an element of randomness. On the other hand, Nersessian's (1992) notion of conceptual change in science involves "abstraction techniques" such as analogy, imagery, thought experiments and limiting case analysis which she defines as the cognitive activities of the scientists. These cognitive activities, however, miss the random nature of scientific discovery. Conceptual change is a post-revolutionary idea. Only after the conceptual change with many elaborations

has taken place does such a change become clear to everyone including the author of the change. In other words, the element of randomness is an integral part of conceptual change in science. Nersessian's (1992) abstraction techniques treat conceptual change logically (non randomly) when from our point of view, it is the individual's investigator's psychology of learning which provides the random element.

Educational Implications

Traditional teaching in mathematics and science seldom promotes learning by mistakes in the sense described earlier. Rather it emphasizes induction and deduction as "the method" for students to learn. Accordingly, students do not recognize the making of mistakes as a legitimate and necessary part of their learning. Mistakes are something you strive to eliminate, minimize or reduce rather than explore. More recently others have viewed the students' making of mistakes as fundamental to learning. For example, Kenealy (1989) not only sees mistakes as central to the process of science, but to the process of learning and the process of teaching as well. He states: "They (mistakes) are flowering of attempts to connect and express ideas and are of enormous value in the process of learning and the process of teaching". (P. 213) Support for this position comes from our own experience as teachers of science and mathematics. We learn when we teach because we discover our mistakes from the students' mistakes. One of us had his college students work with 5th graders during college class time and noted that the college students learned from the mistakes of the 5th graders and vice-versa.

Thus,we re-discover science in teaching because we discover all the mistakes made by ourselves and our students.

Consistent with the Young and Mermelstein (1992) model, ideally problems should be generated by the student. For in attempting to define a problem, the student generates mistakes and develops organs of perception - the student's thinking process. However, practical limitations may restrict students' defining problems and it is the teacher who by generating mistakes models the appropriate strategy for developing students' thinking.

Traditional teaching identifies the process of science as a methodology: the design of experiments to test various hypotheses. This methodology is assumed to be independent of the individual investigator and thus precludes focusing on the investigator's psychology of learning and avoids the need to examine not only the student's psychology of learning but the teacher's as well. Recently, a shift from teaching the "scientific method" to focusing on the cognitive activities of scientists (Newton, Galileo, and Faraday) who have constructed new conceptual structures has been advocated. Nersessian (1992) suggests that a model of the historical process that demonstrates conceptual change (new conceptual structures) resembles conceptual change required in the student's learning of science. In "mining" the history of science Nersessian (1992) suggests that heuristics such as thought experiments and analogy be taught to students. Yet at the end of her paper she states: "As a philosopher and historian of science I cannot speak with any confidence about specific ways to go about incorporating the knowledge we gain from the historical cases into pedagogical techniques. I do hope my discussion will persuade some science educators to take up the task". (P.65) In other words, the educational implications from the historical cases are not clear. We suspect that the reason for this rests on Nersessian's assumption that the model of the historical process provides a model for the learning activity itself. What is missing from Nersessian's view of the historical process is the element of randomness in investigator's psychology of learning. Unless incorporated and what is in fact advocated is a method which is independent of the investigator's psychology of learning and thus precludes implications for the student's psychology of learning.

Summary and Conclusions

In our earlier paper we indicated how Berkson & Wettersten (1984) demonstrated how Popper's scientific methodology, while denying a personal psychology of learning, nevertheless, incorporated it. Central to Berkson and Wettersten (1984) analysis is their thesis that the psychology of learning constitutes an integral part of Popper's Falsification Methodology. Young and Mermelstein (1992) demonstrated that the psychology of learning must be individual and extended the work of Berkson & Wettersten by showing that the Process of Science could be described in the four phases.

In the present paper, we provided further evidence that while Popper's Falsification procedure is a good formula in methodology, it is necessary to include the investigator's psychology of learning in the Process of Science.

Secondly, we suggested that student learning processes in science and mathematics should not be solely identified with scientific methodology, but rather these processes should be an interaction of psychology and methodology. Thirdly, students should be made aware of the importance of mistakes in learning and that teachers should demonstrate this importance in their teaching. Finally, we have suggested how misconceptions regarding the Process of Science, for example, the failure to acknowledge the individual scientist's psychology of learning, generates misconceptions regarding the process of learning and the process of teaching.

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