Evolution, Equilibration, and Biology Instruction

Anton E. Lawson

Anton E. Lawson is associate professor of science education, Department of Physics, Arizona State University, Tempe 85287, where he has taught since 1977. He received a B.S. (zoology) from the University of Arizona, an M.A. (biology) from the University of Oregon, and a Ph.D. (science education) from the University of Oklahoma. He has also done graduate work at the College of Notre Dame and summer work at the Oregon Institute of Marine Biology. Dr. Lawson holds memberships and is active in many professional organizations, including NSTA, AAAS, NABT, NARST, and the Jean Piaget Society. He is associate editor of *School Science and Mathematics*, as well as being the author or co-author of over 100 publications and presentations. He has been conducting teacher training workshops since 1973. In his spare time, Dr. Lawson enjoys playing golf.

A number of articles have appeared here in recent years discussing the relevancy of developmental theory in psychology as a guide for biology teaching (Creager 1975; Green 1978; Lawson, Adi, and Karplus 1979; Lawson and Renner 1975; Lawson 1975; Mallon 1976; Marek and Renner 1979; Walker, Hendrix, and Mertens 1980). An idea from developmental theory seen as most relevant in these articles is that of psychological equilibration—the internal mental process by which individuals develop intellectually. Unfortunately, to date, only very general descriptions of the process of equilibration have been published. Therefore, the primary purpose of this article is to discuss the process of psychological equilibration in enough detail to allow biology teachers to put it to use in the classroom. The process will be discussed against the backdrop of its origin in biological theory of evolution and the thinking of Jean Piaget.

The Basic Assumption

Piaget began his professional studies as a biologist. His psychological theory of intellectual development was inspired by biological theory, particularly theories of embryology, development, and evolution. In point of fact, Piaget's thinking was firmly grounded in the fundamental assumption that intelligence is itself a biological adaptation. Therefore, the same developmental principles should apply to both processes of intellectual development and biological evolution. As Piaget put it, "Intelligence is an adaptation to the external environment just like every other biological adaptation" (Bringuier 1980, p. 114). In other words, the basic assumption is that the development of intelligence during childhood and adolescence can be understood in the same, or analogous, terms as the evolutionary development of a hard protective shell, strong leg muscles, or keen vision.

As biology teachers interested in the development of intelligence in our students, it becomes incumbent upon us to design instruction to supplement the normal process and course of development. This requires that we understand how intelligence develops. The following pages will discuss five major biological theories of evolution, including Lamarck's theory, neo-Darwinian theory, and Waddington's theory of genetic assimilation, as well as the analogous psychological theories of intellectual development drawn from these biological theories. The discussion will focus on genetic assimilation theory and how it provides the best of the available biological theories upon which to base instruction designed to promote intellectual development. It would indeed be a pleasant result if one could say that one's methods of biology teaching were based upon sound psychological theory, which in turn is based upon sound biological theory. It is to this end that the following discussion is offered.

Biological and Psychological Theories

There are at least five biological theories available to explain the evolutionary development of species and, by analogy, five psychological theories to explain the intellectual development of individuals. The biological theories can be termed 1) vitalism, 2) preformism, 3) Lamarckianism, 4) neo-Darwinism, and 5) genetic assimilationism. The analogous psychological theories are: 1) intellectualism, 2) apriorism, 3) associationism, 4) pragmatism, and 5) equilibrationism. The following discussion of each pair draws heavily upon Piaget's analysis in the introduction of *The Origins of Intelligence in Children* (Piaget 1952).

Vitalism/Intellectualism—Vitalism holds that living organisms can arise spontaneously from nonliving substances. Likewise, new evolutionary structures can arise spontaneously due to changes in the environment. By analogy, intellectualism explains intellectual development by endowing the child with an innate ability to construct knowledge by mere consideration of his own activity. In other words, knowledge is derived from reason and reason is the final arbitrator of what is reality: "I think, therefore, I am."

In spite of the seemingly spontaneous appearance of maggots in rotting flesh and microorganisms in stagnant broth, vitalism was defeated long ago by the classical experiments of Redi, Spallanzani, and Pasteur. These experiments showed convincingly that life arises only from prior life. Thus following our basic assumption, it follows that vitalism is not a viable theory upon which to build psychological and instructional theories.

Preformism/Apriorism—The theory of preformism, which gained popularity among 17th and 18th century biologists, asserts that if a structure seems to appear during embryological development, it must have been there all along only in an invisible or microscopic form. Biologists know that leaves and, in some cases, parts of flowers, can be seen folded up inside buds long before they start growing and spreading. Furthermore, in the pupal stage all the parts of the butterfly can be discovered curled up inside. The preformists believed that something like this existed curled up in the egg (or in the sperm) and that embryological development was merely the unfolding and growing of tiny preformed parts. Preformism, when applied to evolutionary development, holds that new structures have a purely internal origin and become observable simply by coming in contact with new environments.

Apriorism, the psychological analogue to preformism, considers new ideas to be innate, thus prior to experience. Experience simply gives the ideas the opportunity to manifest themselves but in no way contributes to their form. Although apriorism has had illustrious proponents, no less than Plato himself, its time has come and gone in psychology as has the theory of preformism in embryology. Alas, more recent microscopic views of egg and sperm cells fail to reveal tiny preformed people curled up inside.

Lamarckianism/Associationism—The third evolutionary theory, Lamarckianism, holds that organisms acquire new characteristics in response to environmental pressures and these new characteristics become hereditarily fixed, thus passed from parent to offspring. The process has been termed the "inheritance of acquired characteristics" (fig. 1).

The analogous psychological theory, known as associationism, claims that intellectual development results from the direct acquisition of habits without mediation by internal mental structures. In other words, new mental structures result directly from the incorporation of habits acquired through experience. Thus, mental structures have a purely external origin. Of course, as any graduate of high school biology knows, Lamarck's theory (at least as generally understood) has fallen by the wayside as have vitalism and preformism. This fact alone may not cause one to reject associationism as a viable theory of intellectual development, yet if we hold to the basic assumption that intellectual

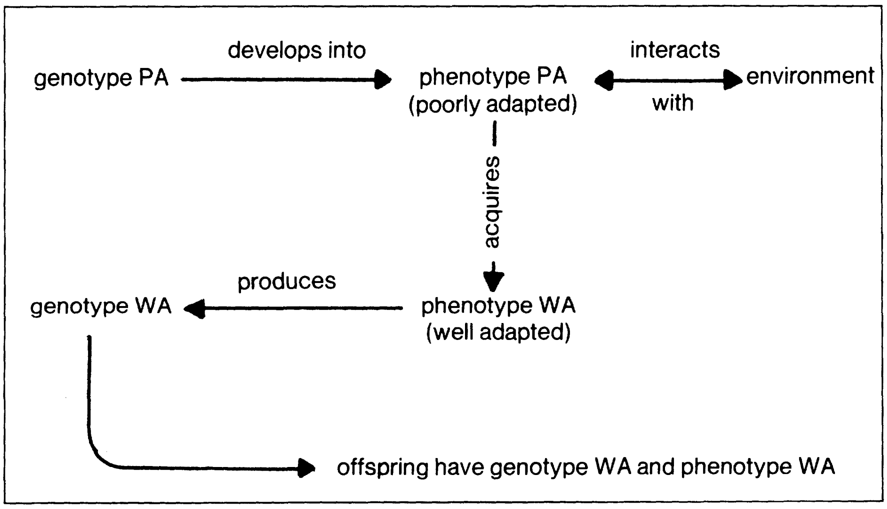

FIGURE 1. Lamarck's theory of the inheritance of acquired characteristics. An organism with a specified genotype (PA) develops into an organism with a corresponding phenotype PA. The organism then interacts with the environment which reveals the initial phenotype to be poorly adaptive; thus the organism acquires the well-adapted phenotype WA (e.g., strong muscles). In some unspecified way the new well-adapted phenotype then acts to modify the initial genotype PA to produce a new genotype WA which is then transmitted to the next generation offspring and produces the WA or well-adapted phenotype.

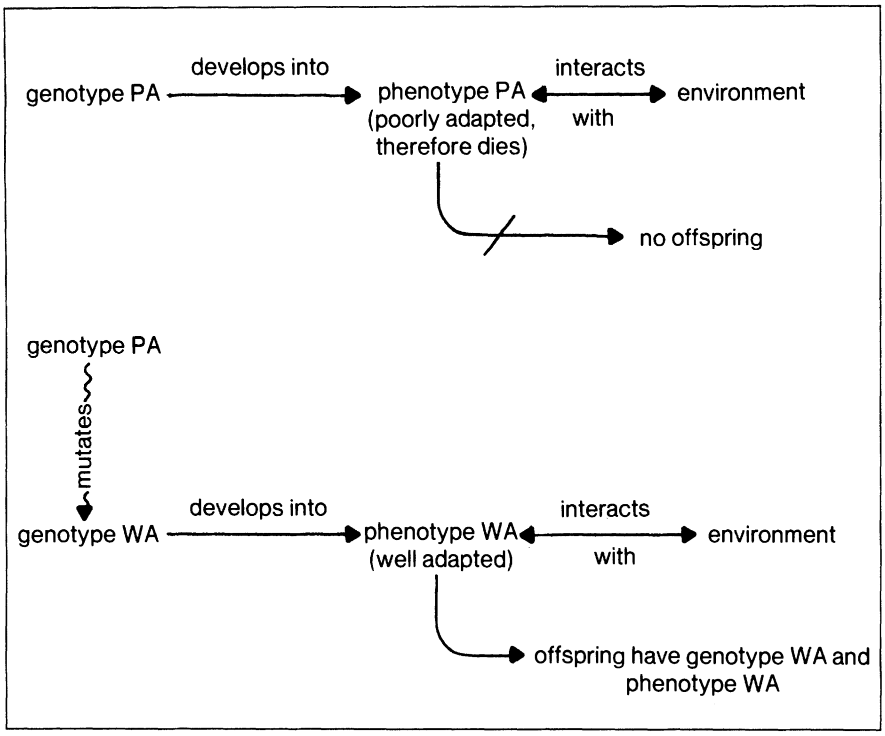

FIGURE 2. Neo-Darwinian theory of evolution through mutation and natural selection. Within a population of organisms, genotypes vary by genetic recombination of initially spontaneous and random nondirectional mutations. Consider genotype PA. It develops into phenotype PA which interacts with its environment. In that phenotype PA is poorly adapted; it dies and fails to leave offspring. But genotype PA may mutate to produce genotype WA which develops into phenotype WA which interacts successfully with the environment and leaves offspring also with the well-adapted genotype WA.

development should be explained in the same, or analogous, terms as evolutionary development, then it must be rejected.

Neo-Darwinism/Pragmatism—The fourth theory, known as neo-Darwinism (neo- because Darwin knew nothing of the mechanics of genetics or mutations at the time he wrote *Origin of Species)* is held by biologists who believe that evolution occurs through a natural selection of already-existing genetic variations initially produced by spontaneous mutation. Mutations in the genome cause changes in observable characteristics which are then selectively evaluated by the environment (fig. 2).

The psychological analogue to neo-Darwinism is pragmatism, in which new behavior arises by random, nondirectional changes in mental structures which are then tried out through behavior. Behavior is found to be either successful and retained or unsuccessful and relinquished. Thus, successful behavior arises as a consequence of trial and error and selection after the fact. New mental structures are internal in origin but the environment plays an active role by selecting only the appropriate structures for retention.

The validity of neo-Darwinian theory is undisputed among modern biologists, yet many readily acknowledge that after-the-fact natural selection is by no means the final word. There are a number of instances of biological adaptation that cannot be explained solely in terms of neo-Darwinian theory. Piaget himself investigated the adaptation of a variety of aquatic snails to wave-pounded and calm environments in which changes in shell shape cannot be explained solely by an after-the-fact natural selection (Piaget 1929a, 1929b). Let us consider these data in some detail for they clearly show a limitation of neo-Darwinian theory and the need to consider the fifth biological theory, genetic assimilationism. Only then will we be in a position to advance a psychological theory upon which to base biology instruction.

Assimilationism/Equilibrationism—Snails of the genus *Limnaea* are found in almost all European lakes including those in Switzerland where Piaget made his initial observations. These snails are famous for their variability in shell shape. Those that live in calm waters show an elongated shape while those that live on wave-battered shorelines develop a contracted, more globular shape (fig. 3).

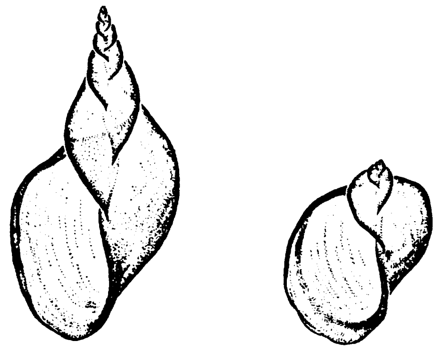

FIGURE 3. Snails of the genus *Limnaea* studied by Piaget. (A) The elongated form, *L. stagnolis*, found in calm waters, (B) The contracted form, *L. bodamica*, found near wave-battered shorelines (from Waddington 1975).

Piaget was able to demonstrate that offspring of the elongated forms, when reared in laboratory conditions simulating the wave-battered shoreline, develop into the contracted form. The contracted form is due to a contraction of the columellar muscle to hold the snails more firmly to the bottom whenever a wave threatens to dislodge them. As a consequence of muscle contraction, the shell develops a contracted form as it grows. Thus the contracted form is a phenotypic adaptation without genotypic change. Interestingly, however, this phenotypic adaptation has become genetically fixed in naturally occurring populations. This was discovered by taking contracted forms into the laboratory and rearing their eggs in calm conditions. The offspring retained contracted phenotypes through many generations. This is an excellent example of a characteristic acquired in the course of a lifetime that has become genetically fixed. This clearly appears to be support for Lamarckianism.

Can neo-Darwinian theory adequately explain the phenomenon? I think not. The key argument (Piaget 1952, 1975, 1978) rests on the fact that the elongated snails, when placed into a wave-battered environment, are able to acquire the contracted form. In other words the contracted form is an acquired (non-hereditary) adaptation. Thus, in the past when the elongated forms moved into wave-battered environments, there would be no need for a natural selection for the contracted form to make it a hereditary genotypic trait. In fact, a natural selection for snails having the contracted genotype would seem to be impossible because there would have been nothing to select. All of the snails with either genotype would be contracted! How then did the contracted phenotype become incorporated into the genome?

Genetic Assimilation

The generally accepted answer to this question draws heavily on the work of Waddington and his theory of genetic assimilation. It should be pointed out that, although Waddington's theory allows for the assimilation of genes insuring the inheritance of initially acquired characteristics, it does so through natural selection, but not of the relatively simple sort envisioned by Darwin. In reality, the theory of genetic assimilation represents a further differentiation of neo-Darwinism rather than a contradiction of it.

Genetic assimilation involves a natural selection of individuals with a tendency to develop certain beneficial characteristics and, as such, represents a widely accepted and valid model of gene modification which appears as a matter of course in modern textbooks of evolutionary biology (e.g., Ehrlich, Holm, and Parnell 1974; Futuyma 1979). In order to understand Waddington's theory of genetic assimilation it is necessary first to consider embryological development and Waddington's concept of canalization.

Canalization

The fertilized egg is but a single cell. As it divides, the resulting cells differentiate into the myriad of cell types such as skin, brain, and muscle cells that constitute the newborn. The developing embryo has a remarkable ability to buffer itself against environmental disturbances to insure that "correct" types of cells are produced. This is evidenced even before the first cell divides. For example, many eggs contain particular types of cytoplasm arranged in definite places. When such an egg is centrifuged, the types of cytoplasm are displaced. But if the egg is then left alone, the types of cytoplasm begin gradually to move back to their original places. This self-righting tendency is also found in eggs which are cut in half. Identical human twins are produced by one egg that divides in an abnormal way so that each twin arises from what one would expect to be able to produce only half of a normal individual.

The term Waddington gives to the developing organism's ability to withstand perturbations to the normal course of development is "canalization." As Waddington (1966) describes it:

> The region of an early egg that develops into a brain or a limb or any other organ follows some particular pathway of change. What we have found now is that these pathways are 'canalized', in the sense that the developing system has an inbuilt tendency to stick to the path, and is quite difficult to divert from it by any influence, whether an external one like an abnormal temperature or an internal one like the presence of a few abnormal genes. Even if the developing system is forcibly made abnormal—for instance, by cutting part of it away—it still tends to get itself back onto the canalized pathway and finish up as a normal adult. (p. 48)

Waddington goes on to point out that canalization is not complete. The developing system will not always end up as a properly formed adult. Yet the important point is that it has the tendency toward self-regulation, toward a final end product, even in the face of considerable variance in the paths taken.

Waddington likens canalization to a ball rolling downhill with several radiating canals opening up in front of it (fig. 4). As the ball rolls downhill, certain internal (genetic) or external (environmental) factors can deflect the ball into one or another canal with the ball ending up at the bottom at one of a finite number of predetermined points. The roll does not terminate halfway up the side of one canal. Waddington calls the system of radiating canals the "epigenetic" landscape. To describe the development of an entire organism, a number of epigenetic landscapes would be required—one for each characteristic.

Suppose, for example, an epigenetic landscape were constructed to represent the development of the sex of an individual. The landscape would contain two canals, thus would dictate one of two final end points—male or female. Genetic factors would then operate to deflect the ball into one of the two canals and the normal adult would end up male or female (but not somewhere in between) despite intrusions which, at intermediate points, might cause the ball to roll part way up the side of one of the canals. The environment might also cause the ball to be deflected into one or the other canal.

An excellent example of this occurs in the marine worm *Bonellia* where the environment determines the individual's sex, but canalization usually insures a male or female—not an intersex. Figure 5 shows the female and male *Bonellia* worms. The larvae are free-swimming. If the larva settles down alone, it develops into a female. If, however, it lands on the proboscis of a female, it develops into a dwarf male.

According to Waddington, organisms vary in their ability to respond to environmental pressures due to differences in their epigenetic landscapes, i.e., their degree of canalization, the heights of thresholds, and number of alternative canals. Some individuals have well-canalized landscapes with few alternatives, hence are relatively unresponsive to environmental pressures. Compare the two epigenetic landscapes shown for the two first-generation individuals in figures 6a and 6b. Both individuals have well-canalized landscapes and have two alternatives, yet the threshold in early development of landscape H is higher than that in landscape L. Hence, an environmental pressure, depicted by the non-shaded arrow, will most likely fail to force the ball across the high threshold in H to produce the developmental modification (WA). On the other hand, in landscape L with its lower threshold, the same environmental pressure is more likely to push the ball over the threshold into another canal and produce the developmental modification.

Because of such differences, individuals vary in their ability to respond to environmental pressures. Thus, some may acquire beneficial modifications, while others may acquire nonbeneficial modifications, and some may not be easily changed. Of course, those that acquire the beneficial modifications have a better chance for survival and will leave more offspring. The poor responders will die out. Hence landscape L and the characteristic of being able to respond in a certain beneficial way is selected.

As shown in the figure, the population becomes one in which all members have landscape L. At this point only the slightest genetic mutation (shaded arrow) now can serve to push the ball over the threshold into the new canal. Once this happens the organism will develop the well-adapted phenotype WA with or without the environmental pressure. In a sense, the selection for landscape L has put the developmental machine on hair trigger. Any number of gene mutations, which can be considered random at the level of nucleic acid structure, are likely to produce the present well-adapted phenotype. Therefore the mutations are not random in their adaptive effect but may serve to produce modifications in the genome that are positive in their direction. The end result is that beneficial characteristics initially acquired in response to specific environmental pressures are assimilated into the genome. This result appears neo-Lamarckian yet involves mutation and a natural selection for individuals able to acquire the desired characteristics.

Although Waddington (1975) has stated that Piaget's studies of *Limnaea* represent one of the most thorough and interesting examples of genetic assimilation in naturally occurring populations, the biological literature is replete with additional natural and experimental

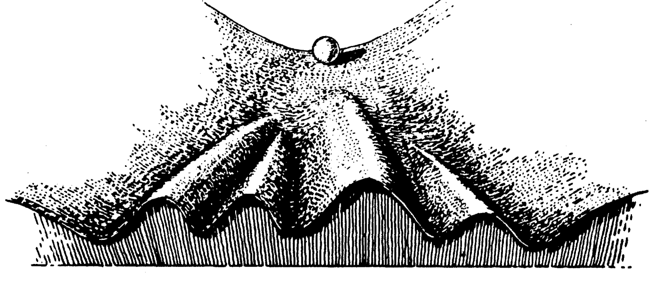

FIGURE 4. The epigenetic landscape of the developing individual. The various parts of a developing embryo have a number of possible canals of development open to them. Genetic or environmental pressures may switch the course of development from one canal to the next, resulting in different observable characteristics (from Waddington 1966).

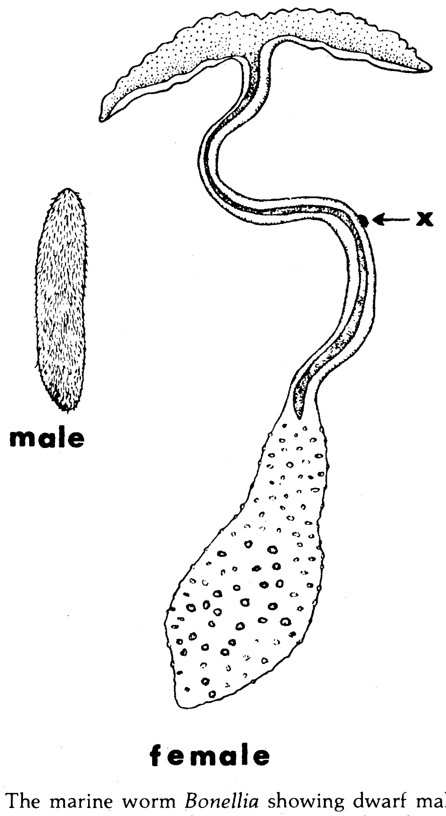

FIGURE 5. The marine worm *Bonellia* showing dwarf male and female forms. The arrow marked X points to the dwarf male (actual size) on the female proboscis (from MacGinitie and MacGinitie 1968).

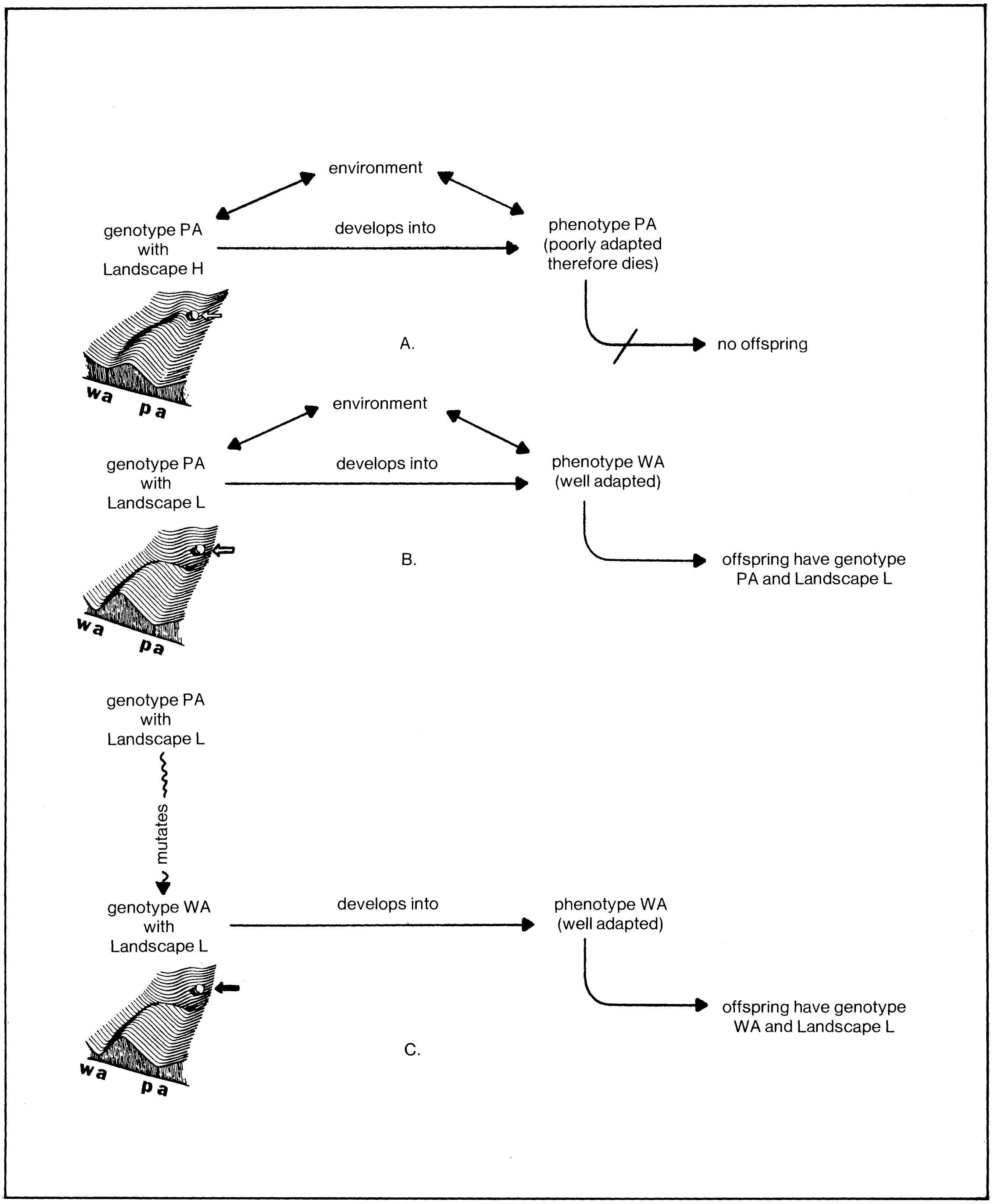

FIGURE 6. Waddington's theory of genetic assimilation. (A) An organism with a poorly adapted genotype and an epigenetic landscape nonresponsive to environmental pressure (non-shaded arrow) will develop into a poorly adapted phenotype which is selected against, therefore eliminated. (B) An organism with genotype PA and a responsive landscape L acquires a well-adapted phenotype as the environmental pressure (non-shaded arrow) is able to push the course of development across the threshold into the WA canal. However, the well-adapted phenotype has yet to be assimilated into the genome, and the offspring will exhibit the new phenotype only in the presence of continued environmental pressure. (C) Genotype PA with landscape L spontaneously mutates (shaded arrow) to produce new genotype WA which produces the phenotype WA even without continued environmental pressure (i.e., the initially acquired characteristic has been genetically assimilated).

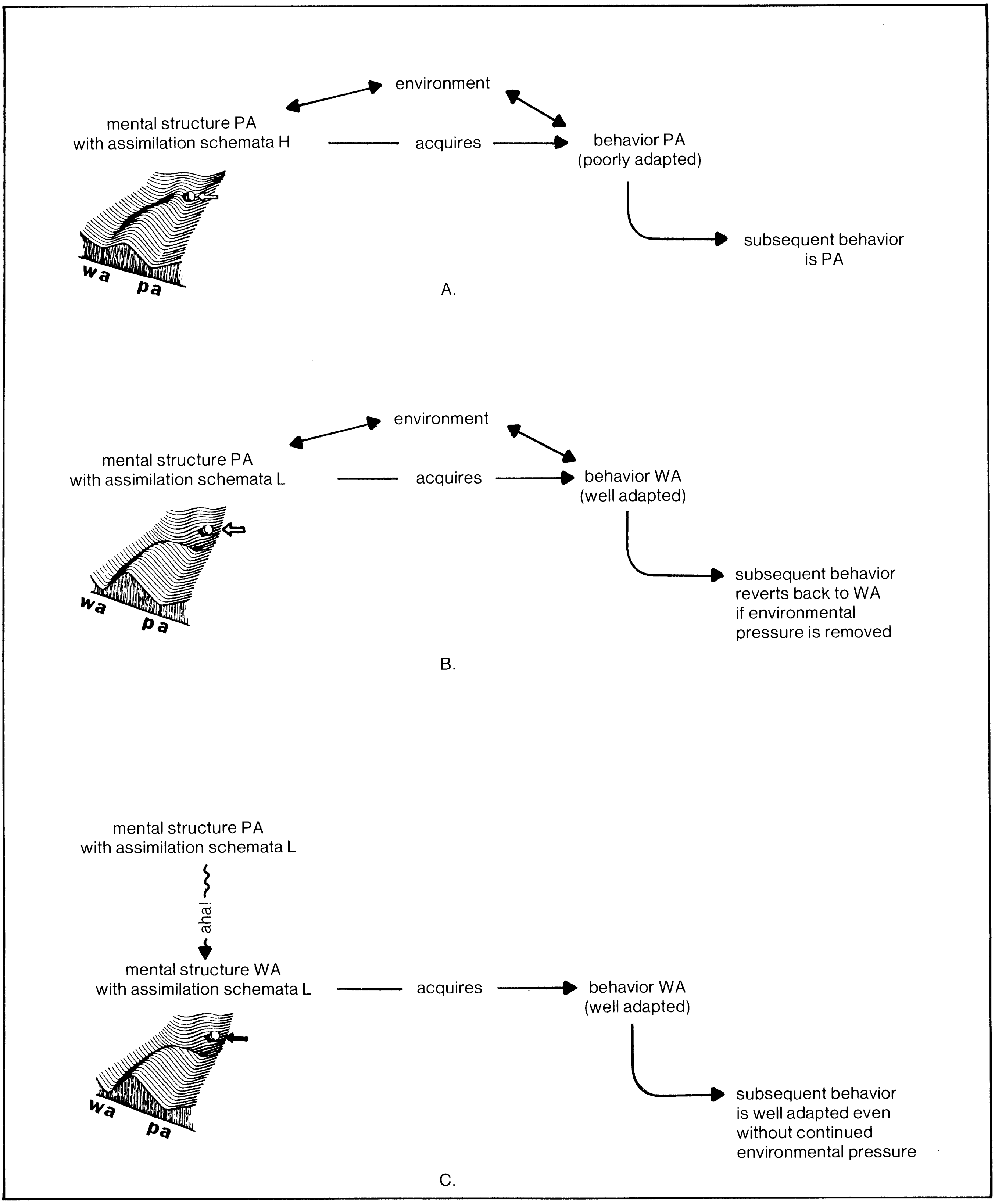

FIGURE 7. Psychological equilibration seen as analogous to Waddington's theory of genetic assimilation. (A) An individual with mental structure PA and inadequate assimilation schemata H interacts with the environment and continues to exhibit poorly adapted behavior PA. (B) An individual with mental structure PA and adequate assimilation schemata L interacts with the environment and acquires a new well-adapted behavior WA. However, the new behavior has not been assimilated into the present mental structure and will be relinquished without continued environmental pressure. Disequilibrium exists. (C) The individual with mental structure PA and schemata L undergoes an "aha" experience (the new environmental input finally makes sense to him in light of what he already knows). The mental structure is accommodated to allow the complete assimilation of the input. Subsequent behavior is well adapted even without continued environmental pressure.

demonstrations of its validity. The now classical experiments of Clausen, Keck, and Hiesey (1948) suggest genetic assimilation at work in the development of the plant *Achillea lanulosa* at various altitudes in the Sierra Nevada Mountains of California. Low altitude plants are taller than those found at higher altitudes but when the seeds of low altitude plants are planted at high altitudes, the plants become dwarfed just like the ones naturally occurring in the high altitudes. Thus dwarfing is initially an environmentally acquired characteristic. By planting the seeds of naturally occurring high altitude dwarfs in gardens at low altitudes, Clausen, Keck, and Hiesey found that the seeds developed into dwarfed plants even though the high altitude environmental pressure had been removed, i.e., the dwarfed form had been genetically assimilated.

Waddington (1959) studied genetic assimilation in the laboratory through a series of natural selections of fruit flies raised on mediums with high concentrations of salt. He was able to produce a population of fruit flies in which genes for large anal papillae (known to assist the regulation of osmotic pressure of body fluids) were assimilated. The development of large anal papillae, like the contracted shell shape and dwarfed plant height in the previous examples, was shown to be a phenotypic adaptation in response to direct environmental pressure; with selection for genes insuring this phenotypic adaptation, it became genetically assimilated. Additional examples can be found in Rendel (1967) and Futuyma (1979).

Psychological Equilibration

[The following discussion of psychological equilibration differs in subtle ways from Piaget's conception of the process in that Piaget's conception is based upon his concept of biological phenocopy (see Bringuier 1980, p. 113; Piaget 1978, pp. 78-83; and Piaget 1975, pp. 216-217). As far as I am aware, Piaget's concept of phenocopy has failed to receive any favor among modern biologists, therefore the present discussion of psychological equilibration will be confined to its relationship to the generally accepted theory of genetic assimilation.]

The psychological counterpart to genetic assimilation can be termed psychological equilibration. Figure 7 explicates the equilibration process as a process analogous to Waddington's theory of genetic assimilation. Again the psychological analogue to the changing genotype during evolution is the developing mental structure during one's lifetime. The epigenetic landscape '(itself shaped by the genes) corresponds to one's predisposition to acquire new behaviors determined by what Piaget (1971, p. 22) has called "assimilation schemata." The phenotype corresponds to overt behaviors. Figure 7a corresponds to a situation in which the individual with assimilation schemata H simply will not respond to pressures imposed by experience and will not develop a new mental structure (WA). Interaction with the environment does not produce "disequilibrium" or subsequent mental accommodation. The individual is not "developmentally ready" because the assimilation schemata available to the individual are not adequate to assimilate the new experience. The available assimilation schemata are built up by the interplay between the individual's powers of coordination and the data of experience. Note that such an explanation dictates incremental and sequential development.

Figure 7b on the other hand, indicates that the individual with assimilation schemata L is able to respond to environmental pressures and acquire a new behavior. But the newly acquired behavior has not yet been assimilated into his mental structure (i.e., the mental structure remains PA). The new behavior and the person's previous ways of thinking have not been integrated. The result is mental disequilibrium. With removal of environmental pressure, the individual is apt to revert to previous inappropriate behaviors just as the offspring of genetically elongated but phenotypically contracted snails will develop into the elongated form if reared in a calm environment.

In the classroom a student may be able to correctly solve a proportions problem if the teacher is there to suggest the procedure to him or if the problem is similar enough to ones previously solved. But if left to his own devices, use of the proportions strategy may never occur to the student because he has failed to comprehend why it was successful in the first place (i.e., it has never been integrated with previous thinking). Thus figure 7b can be said to represent a state of disequilibrium because a mismatch exists between the poorly adapted mental structure and the sometimes successful behavior.

Finally figure 7c represents the restoration of equilibrium through a spontaneous, internal, yet directional, reorganization of mental structure which allows the complete assimilation of the new behavior pattern into the accommodated mental structure of the individual. Thus psychological assimilation corresponds to the entire process of the incorporation of new well-adapted behavior patterns (phenotypes) into one's mental structure (the genome) by way of a spontaneous accommodation of mental structure (i.e., the mutation). Hence, one does not have assimilation without accommodation. Piaget was fond of quoting the child who, when asked about the number of checkers in two rows of unequal length, responded correctly and reported that "Once you know, you know forever." Here is a child with an accommodated mental structure who had completely assimilated the notion of conservation of number.

The Importance of Equilibration Theory for Instruction

The importance for instruction of the psychological theory of equilibration can be simply stated. If one adopts the vitalism/intellectualism or preformism/apriorism positions then the teacher is superfluous to aid in the student's intellectual development. The teacher can do nothing but wait for the proper mental structures to develop. On the other hand, if one adopts the Lamarckian/associationism position all one would need to do is force students to work by rote problems that required the appropriate behaviors for solutions. The mere habit of correctly working these problems would insure that the corresponding appropriate mental structures would develop. Of course, teachers know that such a procedure simply does not work. As Ausubel (1979) has correctly pointed out, faculty psychology or the "formal discipline" approach to education has long been discredited.

If one adopts the neo-Darwinian/pragmatism approach to education then one is forced to wait until spontaneous and nondirectional reorganizations of mental structures occur before intellectual development will take place. Again the entire process is internal and not amenable to environmental-instructional shaping. The teacher is relegated to the relatively unimportant position of simply telling a student when his ideas are right or wrong and is in no way able to shape the direction of the student's thinking.

But if one adopts the psychological analogue of genetic assimilation theory, then the teacher is placed in a position of not having to sit idly by and wait for intellectual development to occur. The teacher knowledgeable of developmental pathways can produce the environmental pressure which places students into the position of being able to spontaneously reorganize their thinking along the path toward more complex and better adapted thought processes. The teacher can be an instigator of disequilibrium and can provide the pieces of the intellectual puzzle for the students to put together. Of course the ultimate mental reorganization will have to be accomplished by the students but the teacher is far from passive. He can set the process on hair trigger just as the directional natural selection of Waddington sets the genome on hair trigger to await the slightest mutation.

The key point is that external knowledge (that presented by the teacher) can become internalized if the teacher accepts the notion that the equilibration process is the route to that internalization. This means that the student 1) must be prompted to engage his previous ways of thinking about the situation to discover how they are inadequate to assimilate the new situation, and 2) must then be given ample opportunity to think through the situation to allow the appropriate mental reorganization (accommodation), which in turn allows the successful assimilation of the new situation (c.f., Karplus *et al.*, 1976).

Consider the well-known case of the high school and college students who employ an additive strategy to solve a proportionality problem. Given two plastic cylinders equal in height but unequal in diameter, the students note that water from the wide cylinder at the fourth mark rises to the sixth mark when poured into the narrow cylinder. When asked to predict how high water at the sixth mark in the wide cylinder will rise when poured into the narrow cylinder, the students respond by predicting mark 8, "because it rose 2 marks last time so it will rise 2 marks again."

. . . the teacher is not a teller. He is a director of learning.

How can these students be taught to use a proportions strategy? According to equilibration theory, they must first discover the error of their previous thinking. In this case this is quite simple to do. Simply go ahead and pour the water into the narrow cylinder and let the students note the rise to mark 9. Even without pouring, the error can be discovered by considering the process of pouring from the narrow cylinder to the wide one. The students predict that water at 6 in the narrow will rise to 4 when poured into the wide. They predict that water at 4 in the narrow will rise to 2 in the wide. They will predict that water at 2 in the narrow will rise to 0 in the wide. Aha, the water disappears! Of course the students see the absurdity of the situation and are forced into mental disequilibrium.

At this point, the students are prepared for step 2, the introduction of the "correct" way to think through the problem. Keep in mind, however, that according to the analogy it is the student himself who must undergo a mental reorganization to appreciate your suggestions and assimilate the new strategy. This will *not* happen immediately. Our experience suggests that this requires considerable time and a repeated experience with the same strategy in a number of novel contexts (c.f., Lawson and Lawson 1980; Wollman and Lawson 1978). The fact that the use of a variety of novel contexts is helpful (perhaps even necessary) is an argument in favor of breaking down some of the traditional subject matter distinctions. For example, in my biology course of preservice teachers I do not hesitate to present problems that involve proportions in comparing prices at the supermarket, altering recipes in cooking, comparing the rotations of coupled gears, balancing weights on a balance beam, estimating the frog population size in a pond, comparing the relative rates of diffusion of chemicals, and estimating gas mileage. If I were to confine the range of problem types to traditional biology subject matter, I suspect that many students would fail to undergo the necessary mental reorganization to internalize the proportions strategy.

Although the previous example dealt with learning to use a proportions strategy (an aspect of logico-mathematical knowledge), equilibration theory does not deal only with the acquisition of logico-mathematical knowledge. As Piaget (1975, p. 212) points out, "Now it is essential to note that this tendency to replace exogenous knowledge by endogenous reconstructions is not confined to the logico-mathematical realm but is found throughout the development of physical causality."

A lovely classroom example of using equilibration theory to help students develop physical understanding was reported by Minstrell (1980). He was interested in teaching his high school physics students about the forces that keep a book "at rest" on a table. Before simply telling the students that the book remains at rest due to the presence of the equal and opposite forces of gravity (downward) and the table (upward), Minstrell asked his students what forces they thought were acting on the book. Many of the students believed that air pressing in from all sides kept the book from moving. Others imagined a combination of gravity and air pressure pushing downward. A few students also thought that wind or wind currents "probably from the side" could affect the book. The most significant omission seemed to be the students' failure to anticipate the table's upward force. Although some students did anticipate both downward and upward forces, most believed that the downward force must total more than the upward force "or the object would float away."

After the crucial first step of identifying the students' initial misconceptions, Minstrell then took the class through a carefully planned sequence of demonstrations and discussions designed to provoke disequilibrium and initial mental reorganization, stopping along the way to poll the students for their current views. The key demonstrations included piling one book after another on a student's outstretched arm and hanging a book from a spring. The student's obvious expenditure of energy to keep the books up led some students to admit the upward force. When students lifted the book already supported by the spring, the initial response was surprise at the ease at which it could be raised. "Oh my gosh!" "There is definitely a force by the spring." Although Minstrell admits that the series of demonstrations was not convincing to all, in the end about 90% of his students voiced the belief that there must be an upward force to keep the book at rest. Of course instruction did not stop here. Nevertheless the majority of Minstrell's students were well on the way to the appropriate mental reorganization.

In short, the teacher becomes an asker of questions, a provider of materials, a laboratory participant, a class chairman and secretary. He gathers the class together and solicits the data they have gathered and their meaning. Most importantly, the teacher is not a teller. He is a director of learning. If materials are well chosen, questions are posed, and students are prompted to think through data and problems, then much can be done to encourage the development of the adaptive mental structures about which we have been talking. How often have you heard teachers complain that their students fail to apply what they have supposedly learned? Perhaps if these teachers took equilibration theory seriously they would have less to complain about.

In conclusion, it seems to me that the important point made by the present conception of intellectual development is that it is the only one that allows for, indeed demands, the possibility that the environment shapes the mind, yet acknowledges that it is the mind itself which determines the ultimate form. In other words it's a two-way street. The biology teacher would do well to remember that you can lead a cognitive horse to water but you cannot make him think.

Acknowledgments—I wish to thank David Rasmussen for his assistance in tracking down information on the theory of genetic assimilation and for his very helpful comments on an earlier draft of this manuscript. Thanks are also due to Bill Tillery, Warren Wollman, and David Hestenes for their comments and to Bonnie Johnson and Karen Alexander for typing the manuscript.

References

AUSUBEL, D.P. 1979. Education for rational thinking: A critique. *In* Lawson, A.E. (ed.) *The psychology of teaching for thinking and creativity.* AETS 1980 Yearbook. Columbus, Ohio: ERIC/SMEAC.

BRINGUIER, J. 1980. *Conversations with Jean Piaget.* Chicago: University of Chicago Press.

CLAUSEN, J., KECK, D., and HIESEY, W. 1948. *Carnegie Institute Washington Publication 581.*

CREAGER, J.C. 1975. Plaudits for Piaget—and some implications for teachers. *American Biology Teacher* 37(8): 463.

EHRLICH, P.R., HOLM, R.W., and PARNELL, D.R. 1974. *The process of evolution.* 2nd ed. New York: McGraw-Hill.

FUTUYMA, D.J. 1979. *Evolutionary biology.* Sunderland, Mass.: Sinauer.

GREEN, M.R. 1978. Learning theory applied to biology education. *American Biology Teacher* 40(5): 268.

KARPLUS, R., LAWSON, A.E., WOLLMAN, W., APPEL, M., BERNOFF, R., HOWE, A., RUSCH, J.J., and SULLIVAN, F. 1976. *Science teaching and the development of reasoning: A workshop.* Berkeley: Regents of the University of California.

LAWSON, A.E., and LAWSON, C.A. 1979. A theory of teaching for conceptual understanding, rational thought, and creativity. *In* Lawson, A.E. (ed.) *The psychology of teaching for thinking and creativity.* AETS 1980 Yearbook. Columbus, Ohio: ERIC/SMEAC.

———., ADI, H., and KARPLUS, R. 1979. Development of correlational reasoning in secondary schools: Do biology courses make a difference? *American Biology Teacher* 41(7): 420.

———., and RENNER, J.W. 1975. Piagetian theory and biology teaching. *American Biology Teacher* 37(6): 336.

———., 1975. Developing formal thought through biology teaching. *American Biology Teacher* 37(7): 411.

MacGINITIE, G.E., and MacGINITIE, N. 1968. *Natural history of marine animals.* 2nd ed. New York: McGraw-Hill.
MALLON, E.J. 1976. Cognitive development and processes: Review of the philosophy of Jean Piaget. *American Biology Teacher* 38(1):28.
MAREK, E.A., and RENNER, J.W. 1979. Intellectual development, IQ, achievement, and teaching methodology. *American Biology Teacher* 41(3):145.
MINSTRELL, J. 1980. Conceptual development of physics students and identification of influencing factors. Unpublished research report, Mercer Island School District, Wash.
PIAGET, J. 1929a. Les races lacustres de la *Limnaea stagnalis* and recherches sur la rapports de l'adaptation hereditaire avec la milieu. *Bulletin biologique de la France et de la Belgique* 62:424.
________. 1929b. Adaptation de la *Limnaea stagnalis* aux milieux lacustres de la Suisse romande. *Revue Suisse de Zoologie* 36:263.
________. 1952. *The origins of intelligence in children.* New York: International Universities Press.
________. 1971a. *Biology and knowledge.* Chicago: University of Chicago Press.
________. 1971b. Problems of equilibration. *In* Nodine, C.F., Gallagher, J.M., and Humphreys, R.H. (eds.) *Piaget and Inhelder: On equilibration.* Proceedings of the First Annual Symposium of the Jean Piaget Society, May.
________. 1975. From noise to order: The psychological development of knowledge and phenocopy in biology. *The Urban Review* 8(3):209.
________. 1976. Piaget's theory. *In* Inhelder, B., and Chipman, H.H. (eds.) *Piaget and his school.* New York: Springer-Verlag.
________. 1978. *Behavior and evolution.* New York: Random House.
RENDEL, J.M. 1967. *Canalization and gene control.* London: Logos Press.
WADDINGTON, C.H. 1959. Canalization of development and genetic assimilation of acquired characters. *Nature* 183(4676):1654.
________. 1960. Evolutionary adaptation. *In* Tax, S. (ed.) *Evolution after Darwin: Volume I, The evolution of life.* Chicago: University of Chicago Press.
________. 1966. *Principles of development and differentiation.* New York: Macmillan.
________. 1975. *The evolution of an evolutionist.* Ithaca, N.Y.: Cornell University Press.
WALKER, R.A., HENDRIX, J.R., and MERTENS, T.R. 1980. Sequenced instruction in genetics and Piagetian cognitive development. *American Biology Teacher* 42(2):104.
WOLLMAN, W.T., and LAWSON, A.E. 1978. The influence of instruction on proportional reasoning in seventh graders. *Journal of Research in Science Teaching* 15(3):227.

Need for Caution

. . . from p. 393

References

ARCHENHOLD, W.F., DRIVER, R.H., ORTON, A., and WOOD-ROBINSON, C. 1980. *Cognitive development research in science and mathematics education.* Leeds, England: Center for Studies in Science Education, University of Leeds.
BARMAN, C.R. 1982. Science education for the 80s: Human brain research will make changes inevitable. *American Biology Teacher* 44(4):211.
BOYD, E. 1962. *In* Altman, P., and Dittman, D. *Growth.* Washington, D.C.: Federation of American Societies of Experimental Biology.
EPSTEIN, H.T. 1974. Phrenoblysis: Special brain and mind growth periods. I. Human brain and skull development. *Developmental Psychobiology* 7(3):207-216.
MODGIL, S., and MODGIL, C. 1982. *Jean Piaget: Consensus and controversy.* Eastbourne, England: Holt, Rinehart and Winston.
SHAYER, M., and ADEY, P. 1981. *Towards a science of science teaching.* London: Heinemann Educational Books.

Teaching Theories

. . . from p. 420

OVERTON, W.R. 1982. Creationism in schools: The decision in *McLean versus the Arkansas Board of Education.* [Text of 5 January 1982 Judgment]. *Science* 215:934-43.
PEACOCKE, A.R. 1979. *Creation and the world of science.* Oxford: The Clarendon Press.
PUPIN, M. (ed.) 1969. *Science and religion.* Freeport, N.Y.: Books for Libraries Press.
ROOT-BERNSTEIN, R.S. 1982. On defining a scientific theory: Creationism considered. *In* Montagu, A. (ed.) *Evolution and creationism.* Oxford: The University Press, in press.
________. 1982. Ignorance versus knowledge in the evolutionist-creationist controversy. Paper presented June 22 at the symposium, "Evolutionists Confront Creationists," American Association for the Advancement of Science, Pacific Division, Santa Barbara, Calif.
RUSE, M. 1982. A philosopher at the monkey trial. *New Scientist* 317-319.
SKOOG, G. 1980. The textbook battle over creationism. *Christian Century* 97:974-76.
________. 1982. We must not succumb to specious arguments for equal time. *Education Week* 1(18):19.
ZIMMERMAN, P.A. (ed.) 1970. *Rock strata and the Bible record.* St. Louis: Concordia Publishing House.