The Integrated Laboratory Program for Cognitive Development

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Abstract

I discuss an Integrated Science and Mathematics Laboratory Program designed to actually deal with the problems, so widely found, of lack of basic skills, lack of problem solving ability, non-transition to formal level thinking, non-transfer of knowledge, and inability to apply basic quantitative reasoning and skill to real world situations. I discuss the history, the philosophy, the methodology, and the nuts and bolts of implementing such a program. Interested persons are urged to contact the author.

I. Introduction

Far too many American students operate entirely through rote procedural operations with no comprehension of meaning. The author's *Basic Skills Diagnostic Test* (BSDT, inquiries welcome) has shown that some students in every class lost all meaning in mathematics in middle school. We are graduating millions of students who cannot put fractions and decimals in order. Many readers will be aware of lack of transfer of knowledge, lack of reasoning and problem solving. I take some understanding of the depth of this problem as a given. This paper presents a program with a 25 year record of dealing with this. This program cannot be implemented as a band-aid. It is a major effort and will not be for everyone.

This program originated at Bloomfield College (NJ) in the early 1980's. The authors of this program (O.G. Kolodiy & this author) received in 1980 a grant from NSF to develop a program for cognitive development in math and science. The application cited then new research on how people learn and suggested a program to produce a transition from "concrete level" thinking, characterized by a need for rote learning and an inability to see and manipulate abstract relations, to "formal level" thinking, characterized by an ability to see and use abstraction and to realize the "formal" `identity of apparently different types of problems.

There was already research indicating that traditional lectures are inefficient at producing meaningful cognitive change, and that hands-on, so-called "guided-discovery" programs did a far better job. Though this was well documented 30 years ago, little has changed in most schools. This program is designed to be entirely hands-on and discovery based and thus to give students some higher level reasoning training.

II. History

This program was by no means the first of this genre. In the 1960's a program intended for 8th or 9th grade science was widely used. The *Introductory Physical Science* (IPS) program was also entirely laboratory. Not designed specifically to raise the cognitive level, it was more oriented to teaching specific science content.

In the 1970's a program developed by Arnold Arons was published under the name *The Various Language*. This program was specifically designed to deal with reasoning and cognition and was also strongly discovery based. We were strongly influenced by Arons' program, as well as by Arons' many journal papers on science education. In particular, we recommend a paper in the American Journal of Physics (1973) *Towards a Wider Public Understanding of Science*. Those familiar with Arons' work will find some of his ideas here. Arons' program assumed a level of mathematical sophistication (competence in 9th grade algebra) that our students almost universally did not have. We had already discovered that we had students who didn't know how many eighths of an inch were in an inch. We began some serious probing and found a majority of our students had lost all comprehension of mathematics in the fourth grade. This author (Epstein) has used the BSDT and has shown that very large numbers of students are in this condition. This gap must be filled before any meaningful progress can be made. A report on BSDT results is available from the author.

Thus this program begins where too many students are — fractions and decimals, basics of measurement, place-value numbers and the metric system. For students who test as having real conceptual understanding of these basics and who can use them to solve simple problems, this program can begin a little further on. But many students can pass multiple choice tests and have no usable conception of what they are doing. It is absolutely certain that one cannot go by previous courses taken or grades obtained.

III. Philosophy and Methodology

It is now known from serious scientific studies that lecturing is the most efficient way of transferring information but the least efficient in providing conceptual understanding. It has been assumed that if the necessary information is learned and enough practice drill is given, conceptual understanding will arise spontaneously. But a great many students have a deficit of some *experience* and cannot integrate facts they have learned into a usable structure. This program is designed to help provide the missing experience. It does this by providing a large number of activities where the student must provide his or her own understanding and then test it. It is designed in a "spiral" approach where similar problems and similar materials keep reappearing but at ever higher levels of abstraction requiring ever deeper levels of understanding. It is *never* assumed that when a student has completed a unit of work, the student has mastered the concepts in it. Concepts only become clear, and the mind only gains the power to see the relevance and power of the concept, when it is encountered in a wide variety of contexts and looked at for every possible connection with other concepts already familiar. That is, when it is used in different ways to elucidate different problems and the results can be squared with real experience. This program is not a replacement for any particular math or science course, such as basic algebra or general chemistry. It does *not* provide "Science Literacy" The lumping together of the huge skill and cognition problem with the endless debate over "Numeracy and Science Literacy" has served neither well. The students *do* learn a great deal about how scientific thinking works, but they are not *told* this. They gain understanding by acquiring foundation tools and then by doing investigative lab work. The goal is that the students leave the program with a more powerful mind.

IV. The Student

The program has been used as of 2007, in its original implementation at Bloomfield, at Lehman College of C.U.N.Y., for 10th graders at the Renaissance School (a public high school in Queens, NY), and the early parts of the program have been used with 6th graders in a public school in Chinatown, Manhattan. It has been used for the training of middle school teachers in a New York school district (funded through a grant from NSF to NY state), and with a group of inner city 10th graders in a summer program funded by the Goldman-Sachs foundation. I believe the program to be of exceptional value for teacher training, both for those who must directly experience how guided-discovery teaching works, but also for the considerable number who do not understand the mathematics much better than the students they are teaching.

There were a lot of similarities across populations and a few differences. All except the Chinatown group were operating way behind where the education system assumed them to be. An overwhelming majority of those who were in this program tested as being stuck at the 4th grade level. At Renaissance, we found as the program went on that perhaps 10% of our students didn't know the multiplication tables as far as the 9's, and would do single digit multiplication by adding or counting. In spite of all that has been written in the professional literature and in the popular press, it seems few realize the reality of our student population, at least in the US. The reality must be faced if progress is to be made. Clearly students have gotten through years of mathematics (and science) by memorizing things that have no meaning for them. Students assume that all mathematics and science learning is of this type and are rudely awakened by this program. They cannot get through it, if teaching, testing and journal grading are appropriate, by memorizing rules, and they often do not take kindly to that. It is a prevalent myth that in a well-taught course learning will be easy and students will be happy. This myth is, in my opinion, false and has been destructive to education. We must acquire the consciousness that real growth in the power of the mind, is *very hard work*. But that mastery of a new level of thinking is *tremendously exciting*. Growth of the power of the mind is *never* easy. The best teaching is that which makes it *hard* by *avoiding* superficiality —rote memorizing and symbol pushing.

V. The Teacher

The prerequisites needed to successfully teach this program are in one sense modest and in another sense substantial. The program does not require advanced knowledge of mathematics and science. It does require a *profound* depth of understanding of *elementary* mathematics and basic physical science — what Li Ping Ma called “PUFM” (Profound Understanding of Fundamental Mathematics). Most of all, the teacher, just like the student, must go beyond symbol manipulation and justify all operations and reasoning in conceptual terms. As an example: How can one justify using proportions without falling back on a memorized rubric: “This is to this as that is to that — so make fractions.”? How do I know when to use a proportion and when not to? Most of all, the teacher must be comfortable with open ended and unpredictable events in a discovery based lab program; the teacher needs a repertoire of provoking responses to student difficulties that turn the student’s attention in the right direction without giving cookbook instructions on what to do.

VI. The Laboratory

Much of the program requires a real laboratory space. Table surfaces must tolerate water, salt, simple chemicals. Students need access to sinks and to gas for burners or electric hot plates. Ice is extensively used. Storage areas for a large volume of stuff are essential. A lab period of at least 90 minutes duration is essential. The students are strongly encouraged from the outset to begin work on their own as soon as they come in. They return to the book and pick up where they left off. It should not require some sort of introduction by the teacher each day to get things moving. This aspect has proved the most striking to visitors to the program — the fact that when the instructor opens the door, students just sit down and start to work.

VII. The Methodology

There are no lectures, although on rare occasions, when many are having trouble with the same thing, the teacher can provide some general discussion from the front of the room. Also, when reviewing the end of chapter problems and exercises, the teacher can work with the class all together from the front of the room. However, lecturing is still inappropriate.

At all other times the student teams are expected to function largely independently, asking for help from the teacher as needed, while the teacher circulates around the room. As the teacher can be with only one team at a time, the other teams must be able generally to work on their own. Students often want to be told everything they should do. We encourage them to read the directions in the text. We ask them to explain in their own words what the text is saying. If the team members argue about it, that’s good.

Students may often begin a procedure without understanding and will thus do something that is not a sensible way to deal with the problem. The key to the method is to allow this process to take place, without interference when possible, with the most subtle of prods when progress has stopped. This is not an easy technique to become comfortable with. Teachers are trained to provide clear and precise explanations of exactly how things work, of the most direct way to get answers. This program is designed to work in *exactly the opposite* way. The teacher must allow student to go up blind alleys and make mistakes. The teacher must permit the student to follow a clumsy and inefficient way of approaching a problem as long as the approach makes some internal sense to the student. If the student is doing something that clearly does not make sense, the teacher must find a question to ask or a simple observation to point out that will allow the student to realize on his/her own that it doesn’t make sense. We suggest that the student look at the problem with small whole numbers where the answer can be seen immediately. Then ask the student to verbalize what was the *process* that led to the answer. Often when the answer is obvious (say for small whole numbers) the student does not become conscious of what the process is and thus cannot extend it to a less familiar case (with fractions or decimals). Asking the student to verbalize the process is an *absolutely essential* part of gaining understanding of underlying meaning.

The most common question we ask students is, “Tell me why you are doing that.” I may ask the question whether what they are doing is right or wrong.

When the teacher asks a student a question, a whole set of processes begins. It is essential to allow them to happen. One of the great misconceptions in teaching is that understanding comes when the teacher is talking. I am certain that is rarely the case. Alternatively it is believed that enlightenment comes when the student is talking. Maybe. I suspect that it really comes in the spaces between the words. In my experience the most powerful tool to allow the light to emerge is *silence*. True thinking begins to emerge when all other alternatives have been exhausted. Students associate “thinking” with flipping through file cards in the memory, having experienced (at least in school) little else.

A very common scenario would be: Teacher asks student to justify why he is doing something. Student waits blankly, based on the experience that if he waits, the teacher will answer for him. Still silence from the teacher. Student begins emitting formulaic responses that were once an answer to some question or other. To each, teacher either asks for the reason why or points out a reason why the answer isn’t sensible. Student believes he has reached the point of hopelessness and gives up: “I don’t know,” still hoping that this will prompt the teacher to provide the answer and “teach” him what he needs to know. At this point the student has been so busy searching for an answer, he no longer knows what the question was. “What was the questions I asked?”, I have said countless times. Student realizes he doesn’t know. Question is repeated . . . slowly. At this point one hopes that the student begins to visualize what the question is asking, making a mental model of the question — a crucial step. Finally some guesses emerge with which the teacher can work because they are at least connected in some way to the question, and earlier misconceptions about the subject will begin to appear and can be dealt with.

This process is slow and often tedious. But it is so powerful. One occasionally will see real pleasure and excitement when the student discovers that he can find an answer on his own, or finds that he has grasped just a little bit of meaning — meaning that he will never lose because he has found it himself through struggle. Don’t assume that you will always get this exciting feedback from the student after the process. But you *will* see it; enjoy it when it happens. It is what teaching is really about.

In order for this to work, there has to be no interruption. An inviolable rule is when one student is trying to respond, no other student can call out an answer. One must be absolutely hard nosed on this. When the question is hanging, a mental process begins. Any provision of an answer from the outside, whether from the teacher or another student, and even if correct, kills the process. It should be pointed out that interrupting this process, even though they feel they are helping the one on the spot, is really destructive. If at first no answer emerges, the teacher should *never* provide an answer and (very important) *never* go on to another student. The essence of the method is to ask another question, perhaps simpler, and then work back up to the original problem. Or point out something that turns the student’s mind to an aspect that he hadn’t seen was relevant.

This method of teaching, with access to a concrete model of the concept, is heart and soul of the program.

The best way to become familiar with it is to experience it *as a student*. All of us really gain understanding — of a subject or of teaching — by direct experience, not from words that people tell us.

VIII. A Typical Lab Session

Just to give a little more of the feeling for the process, here is an example of typical interactions that might occur in a lab session. This dialogue is made up but is entirely typical of many I have participated in.
Here “S” means “Student” and “T” means “Teacher”. The first experiment is a pendulum, designed to introduce intuitively the idea of a variable and to bring some realization that you must change only one thing at a time if you want to know what is causative and to what degree:

S: It has changed.
T: What has?

S: The number of swings.
T: The number of swings in a minute?
S: Yes.
T: O.K.
S: What now?
T: What does it say?
S: "Find out which variable has the most effect on the frequency and which the least . . ."
T: So what did you do that made the frequency change?
S: We put on more weight and we made the string longer.
T: How much of the change was caused by changing the weight and how much was caused by making the string longer?
S: [*long pause — silence*] I don't know. There's no way to tell.
T: Seems like not a great strategy, you can't answer the problem you set out to answer.
S: [*another long silence*] You have to change one at a time.
T: Why not try that and see what you can find out?

Notice that we do not tell them what they have done wrong. In fact the teacher here asks them a question that the teacher *knows they cannot answer*. This produces a "cognitive dissonance", as the jargon goes, — something like a question stuck in the throat.. It is a vastly more powerful teaching tool than telling them what they did wrong. This dialogue is so typical of many that I have heard, and again so much more powerful than telling the student what to do.

IX. The Journal and Notebook

Just as the requirement that students in class verbalize what they are thinking, the writing component of the program is *absolutely central* to the way the program works. Students have in the lab a notebook in which they take detailed notes. The teacher initials each notebook page (with date) at the end of each lab session. This also gives the teacher a crucial few seconds to look for things done that are obviously wrong and simply point out to the student that the matter needs some discussion in the next class. From the notebook, the student writes a journal describing all of the experimental activities.. A handout given to the student explains the Notebook and Journal in some detail. Generally we collect and grade the Journals about 10 times in the course of the full program. The notebook pages must be submitted along with the journal as a check that data has not been fudged.

The lab notebook and journal are absolutely essential to the developmental process. This journal is generally the most difficult part of the program for the students and a major job for the staff to read. But it is a critical part of the learning experience. Basically we are convinced that if the student can explain in his/her own words what has happened in the lab and why, can justify the reasoning and the conclusions, and explain the logic to someone *who was never in the lab and has never seen the tex*t, the student really has it. Without this verbalization, the concepts do not solidify in the same way and tend to drift away.

X. ANALYSIS OF RESULTS.

At Bloomfield, an independent analysis of the results was done by a faculty member with some knowledge of statistics not otherwise connected with the project. Two tests of reasoning skills were developed, one for pre-testing and one for post-testing. We used as controls students from the previous year who went through a Freshman Core Program with the same purpose as this course, but not based on this methodology. There were 91 controls. The experimental group went through the course described in the 1981-82 year. There were 95 students in the experimental group.

The groups were compared with the Mann-Whitney "U" test Scores in both groups are ranked from lowest to highest. The "U" value is the sum of the ranks of the members of the group. The null hypothesis is that U and U' are equal. One calculates a number, Z, for the significance of a difference between U and U'. Z is a standard-normal random variable. At the pre-test the control group scored slightly higher, not significant ($Z = 0.13$). At the post-test the experimental group scored dramatically higher ($Z = 2.17$). This is significant at a level of $p < .03$.

We sought opportunities to do follow up studies on the students after they left the core course, this being the acid test of anything that claims to really increase the abilities of the students. Other than some positive anecdotal evidence, we only had one such opportunity, and the results were extremely gratifying. It came when an Accounting professor came to the committee with a proposal for a new "pre-Accounting" Accounting course. She declared that the students couldn't conceptualize what was involved in accounting. Clearly this caused grave concern because the

ILP course was a prerequisite for Accounting. Upon checking the records, we were stunned to find a perfect correlation in the direction we hoped. In all cases the students who were failing accounting had either failed the Core course, or dropped it, or managed to postpone it. The accounting department was not enforcing its own prerequisite. In all cases those who had passed the Core course were succeeding in accounting.

At Lehman College, Ullman & Ellis obtained an NSF grant to develop a discovery based program and used essentially the ILP. Two one-semester sections were run in the year prior to the grant (1992-93) which got through about one-third of the full ILP One section was entirely Freshmen so that we have a population whose progress we could follow. We looked at this population to see how many survived in school. Their survival rate seems significantly higher than the (appalling) norm for Lehman Freshmen.

The populations that have shown the most optimistic results at Lehman are two groups of Freshman Year Initiative students, one in the Fall of 1993 and one in the Fall of 1994, who had declared intentions to major in Nursing. They covered in one semester about 2/3 of the ILP. All were also enrolled in a large lecture course in Chemistry, which gave us an immediate control group. We examined these groups with a pre-test and post-test in basic skills, and we compared them with the other students in Chemistry for grades and for failure rate. The result is very positive. The 1993 experimental group had a mean of 39% on the basic skills test at entrance. This is very poor but probably above average for Lehman students in this Chemistry course. To establish an equivalent control group in Chemistry, we used the results on a CUNY-wide math test to eliminate the weakest students from the control group. The experimental group was 19 students, the controls 88. All who received grades of INC and those W(U) grades who had never attended were eliminated from the study. In the experimental section all but one were Black or Hispanic, all but 3 were female. The Chemistry instructor was not aware of which students were in the ILP. Interestingly, eliminating those who scored lowest on the CUNY-wide math test did not significantly change the failure rate in Chemistry.

The experimental group had a mean of 77% on a closely matched basic skills test at exit -- almost double the initial score. At no time did the students get the initial test back nor were the questions reviewed.

Those in the experimental section had a grade average of 2.49 in Chemistry; 10% got either F or W(U) grades (and one of those two had failed the ILP also). Those not in the ILP had a grade average of 1.72 in Chemistry; 28% got either F or W(U). This seems to be a quite significant difference -- the failure rate was cut by a factor of almost 3 in the experimental group. We have looked to see if a higher percentage of these students than is the norm survived into the Sophomore year and beyond. The results in the second semester of Chemistry are interesting indeed. Our experimental group now scored *lower* than the rest of the Chemistry class, but *are still passing*. I am confident that the ILP kept alive in Chemistry a population that would not otherwise have survived into the second semester, while the weak students in the control group, though comparable at entrance, did not survive. We are pleased that the ILP group continues to pass in Chemistry, albeit with considerable struggle. We think this is a notable outcome.

The group from the Fall of 1994 had a very similar outcome. Their scores on the basic skills test increased from a mean of 40% at entrance to 74 % at exit. The grading in the Chemistry course seems to have been somewhat easier than in 1993. In the control group 19% failed Chemistry, in the ILP group, *none* failed.