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A Situational Pedagogy for Elementary Mathematics

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It is now clear that the NCTM publication in 1989, *Curriculum and Evaluation Standards for School Mathematics*, was successful beyond expectation in focusing attention on the directions American mathematics education should take. But how does one design a complete, self-contained, K-9 curriculum that wholly incorporates and meets these laudable standards?

A reading of the *Standards* reveals an underlying call for "humanism" in the teaching of children, not only in mathematics but in all disciplines. To this writer that reading suggests a mathematics program (and an implicit definition of the word "humanism") in which . . .

- children are continually involved in the process of learning mathematics as participants, not as spectators;

- mathematical ideas grow out of reactions of children to intriguing situations posed by the program (such as pretend situations in early years, situations from elementary science and/or history of mathematics in later years);

- learning of routine arithmetic skills occurs in the process of reacting to the situations posed and not only in rote drill;

- the many facets of mathematics reinforce each other (for example, in the elementary grades) with arithmetic, geometry, and probability each interacting with and clarifying the others;

- having accepted the proposition that no one can master an idea completely on first, or even second, encounter, the main mathematical ideas continue to reoccur in a spiral curriculum in which the ideas are viewed many times from different perspectives and in deeper and more revealing form;

- the teacher relinquishes the role of mathematical authority, becoming a facilitator as the children discuss and investigate ways of dealing with the situations posed; the authority then belongs to logical

thinking and the mathematics as it is developed;

- reliance on language is reduced in the early years to allow development of simple mathematical concepts that only seem complex when "described" in words;

- intuitive logic and thinking skills are developed indirectly through games and story situations that involve cataloging attributes of arithmetic and geometric relations;

- students write their own textbooks in the form of journals that record the high points and discoveries of the lessons.

An example of such a K-9 program now exists (more of which later), but the nagging questions are: How to "sell" such a program to the textbook publishers? To the test makers? To the "mastery" advocates? To the education establishment?

There is a long list of problems in the '90's that thwart wide implementation of such a curriculum, a list to which everyone interested in education can add a favorite. On the list is the *problem of teacher training and retraining*. Some would argue that the need is for a revamping of the teacher training programs in the universities. But in what directions and under what standards? Others would argue for broad programs of *local teacher retraining*. But by whom and with what agendas? Others would prefer to put political pressure on the *test makers* to revise the content and format of the standardized tests, as, for example, is now being done with some success in Japan. But it is clear to many observers that in spite of the *Standards*, we already have a deeply entrenched set of national standards, which are set by the textbook publishers and the test makers, as well as by the inertial carryover of traditional and comfortably familiar curricula and pedagogy in the schools.

Thus it would appear that before any serious reform effort can be mounted in teacher training, in test making and consequently in commercial textbooks, there

must first be a national sense of the *way* children should be taught and *how* they should be involved in the learning process; i.e., we should confront the issues and make a decision about pedagogy.

It is easy simply to say, "We need a pedagogy that provides for continued intellectual involvement of children in the learning process." But to describe fully such a pedagogy, along with its philosophical basis, would require volumes and years of debate. Instead, it might be possible to understand what is meant by "a pedagogy of situations", to coin a label, by looking at some examples of situations and typical reactions of children to them. These examples, taken from an existing complete K-9 program, show how children of various ages can be engaged in intellectual experiences, some of which might not seem to be mathematical by traditional standards. We argue that such situations have strong implications for mathematics, and for other disciplines as well.

Pedagogically rich situations similar to the following examples can be used successfully to teach computational skills and at the same time give students enjoyable experiences with numerical relationships. We will also see non-numerical examples that are more dramatic in their continued stimulation of intellectual involvement at all levels of mathematics.

CHILDREN OF AGES 5 OR 6:

Tell a story about some children in a playground. While telling the story, we draw the above diagram and say, "The children in our story are playing a game." Explain that each child in the playground is represented by exactly one dot, and each dot is for exactly one child. It is not necessary to draw pictures of children; in fact, such pictures might even distract the children from the purpose of the lesson. On other

days, for example, dots might represent ducks in a pond, or marbles in a bag, or numbers, or lines in a plane, etc.

In the game the children are playing each child points to his or her sister(s) and says, "You are my sister." Draw red arrows as indicated below to show how the children responded.

What sort of comments will five or six year-olds make when asked, "What does this picture tell us about the children in the playground?"

1. There are eight children in the playground.
2. D is C's sister.
3. D is a girl. (Why? Because D is someone's sister.)
4. E has no sisters in the playground.
5. A and B are sisters, so that both are girls.
6. G and H did not listen to the instructions. (Why?) They should have pointed to each other because they are both sisters of F. (Let children draw these arrows. Then tell them that now all the children that can say, "You are my sister" have done so.)
7. At this point some child in every group will probably say, "C is a boy." If we ask, "How do you know that?" we get an answer that in adult language goes like this: Suppose C were a girl. Then C would be D's sister. But there is no arrow from D to C. So we see that C is not D's sister, and hence C is not a girl. So C is a boy.
8. There are children from four different families in the playground.
9. C is D's brother. (Now ask students to draw blue arrows for "You are my brother".) They will draw three blue arrows: from D to C, from G to F and from H to F.

In this type of situation young children grapple with

problems of symbolization and the relation of a symbol to the object it represents. They also give beautiful arguments quite like those that are at the heart of mathematics.

CHILDREN OF AGES 6 OR 7:

Tell a story about a boy, Nick, who wanted to be a detective when he grew up. His grandmother makes up a game for Nick when he visits her. She draws this diagram

and tells him the dots are for three rabbits, her poodle, her three cats, three bugs, a squirrel, herself, Nick, and Nick's nose.

She asks, "Can you tell which dot is for which object?" Nick was puzzled, but she assured him that his talents as a detective would help him. "Here are some clues," she says as she draws a red string. "The red string is for animals with four legs. Is the dot for you inside the red string?"

Nick immediately knew the answer; what was it? He also knew that the rabbits, the poodle, the cats and the squirrel were inside the red string, but he didn't know which were which. "What about the dots outside the red string?" One is for Nick, one is for Nick's

nose, one is for grandmother, and the other three are for the bugs." (Why?) "Can you now tell me what dots are for which objects?" Nick was discouraged and his grandmother gave him another clue by drawing a blue string. "The blue string is for all living things that can climb trees." Nick is a great tree climber, and so he knew his own dot is inside the blue string. "But what about those two dots outside both strings?" Nick knew. Do you? (They must be for Nick's nose and grandmother, neither of which climbs trees.)

"Where is my poodle?" (Inside the red string but outside the blue string.) "Where are the three bugs and the three cats?" Nick needs another clue, because he can't tell which dot is for which thing.

"Your last clue, a green string, is for all living things that like to eat meat."

Nick became very excited, because now he knew exactly which dot was for him, since he loved to eat meat.

Which dot is for Nick? Children hearing the story tend to reason somewhat like this: Nick climbs trees and eats meat but doesn't have four legs. So the dot for Nick is the only one that is inside both the blue and green strings but outside the red string. Then Nick thought about the strings and soon was able to identify all the dots. Can you, for example, find the dot for his grandmother? Nick's grandmother likes to eat meat, but can't climb trees and doesn't have four legs. So the dot for her is the only one inside the green string but outside both the red and blue strings. Similar reasoning identifies all the other dots. Why is the dot outside all three strings for Nick's nose? Nick's nose, as a separate object, has no legs, cannot climb trees and does not eat meat. So its dot is outside all three strings.

See the diagram below.

CHILDREN OF AGES 8 OR 9:

Tell a story about a prisoner in a dungeon in a mythical land. The dungeon has three tunnels leading from it. Unknown to the prisoner are these facts:

TUNNEL A LEADS TO FREEDOM AFTER ONE- HALF DAY OF CRAWLING.

TUNNEL B WINDS BACK AFTER TWO DAYS OF CRAWLING TO A CHUTE THAT DUMPS HIM INTO THE POND IN THE MIDDLE OF THE DUNGEON.

TUNNEL C WINDS BACK TO THE SAME POND AFTER THREE DAYS OF CRAWLING.

The king is a sporting fellow; so he gives his prisoners a chance to gain freedom. Each prisoner is given enough food to stay alive for $9/2$ days and are allowed to select any of the three tunnels at random and try to crawl to freedom. What do you think the chances are of this prisoner escaping? (By the way, what the prisoner doesn't know is that if he lands in the pond he will be so confused that he won't know which tunnel he chose before. So he will again have to choose a tunnel randomly, and possibly again, and again — if he has enough food left.)

Children of this age will have met similar situations and will accept a suggestion to simulate this situation with a random device. Suppose they select a spinner such as the one shown below, with equal regions, because all the tunnels are equally likely to be chosen randomly.

Each child then puts himself in the place of the prisoner and selects tunnels by using his spinner. For example, one child might spin and get B (two days elapsed) and then spin again and get C (three days elapsed). So this prisoner does not escape because his food ran out. Another child might get C on the first spin, then A on the second; thus, this prisoner escaped. Still another might get B on the first spin, B

on the second and A on the third; this prisoner also escaped. Putting together the total experiences of the class it might be decided that it is slightly more likely that the prisoner escapes than not, but it also might be too close to tell.

Later, at ages of 11 or 12, the children will have had enough experiences with random experiments to analyze this situation with probability tree diagrams. Using the knowledge that the three outcomes of the spinner are equally likely, that is, that $P(A) = P(B) = P(C) = 1/3$, the children draw a tree such as this,

which records the possible adventures of the prisoner. Why does the sequence of spins B, then B, then B lead to death while the sequence B, then B, then A leads to escape? (The first sequence takes 6 days, while the second takes $4 + 1/2$ days.) Adding the probabilities of escape, $P(A) + P(B,A) + P(B,B,A) + P(C,A) = 1/3 + 1/9 + 1/27 + 1/9 = 16/27$, which is greater than $1/2$. Why is $P(A) = 1/3$? Why is $P(B,A) = 1/9$? Why is $P(B,B,A) = 1/27$? Why is $P(C,A) = 1/9$? (Imagine that 27 marbles are poured into the mouth of a toy in which one-third of them flow into each of three tubes that dump into other tubes, etc., where the same process continues as in the tree diagram. How many of the marbles will follow the path A? (9) The path B,A? (3) The path B, B, A? (1) The path C,A? (3) So 16 of the 27 marbles will end in the escape positions, i.e., $P(\text{escape}) = 16/27$)

CHILDREN OF AGES 9 OR 10:

There has been much argument about the role of hand calculators in elementary mathematics education. Too often these cheap, little machines are thought of as

merely tools for calculation, but in reality they also can have a significant role in thinking about and obtaining insights about number relationships. Here is a dialogue between teacher (T) and students (S) in a class of 9-10 year-old children who have 8-digit displays on their hand calculators.

T: (Draws on board) Who can label this dot (pointing to the first unlabeled dot in the spiral)?

S: 47, because 47 times 1 is 47.

T: The next one? You many use your calculator if you wish.

S: 2209, because 47 times 47 is 2209.

T: Go on.

S: The next one is 103,823. And then comes 4,879,681. And then—what's that funny thing on my screen?

S: On my calculator at home that's the overload symbol.

T: What do you mean by "overload symbol?"

S: That means the number is too big for the machine? It can only work with numbers up to eight digits..

T: Does this mean that we can't do this last calculation on your calculators?

S: Yes.

T: What should we do?

S: Do it by hand.

T: You mean we must use our brains instead of the calculators. Is the calculator of no help with this fifth calculation?

S: I think I know how we can use the calculator to do this problem. First multiply 4,879,681 by 7 and then multiply 4,879,681 by 40 and add the two numbers.

S: That's right. That would be the same as multiplying by 47.

T: Good. Let's try that. What's 4,879,681 times 7?

S: 34,157,767.

T: What should we do next?

S: You'd better write that on the board so we won't forget it, because the calculator will lose it when we do the next part of the problem.

T: Good thinking. I'll record that number while you calculate 40 times 4,879,681.

S: But it overloaded again.

S: That's OK. We can multiply 4 times 4,879,681 on the calculator and then multiply that by 10 by putting a "0" at the end to get 195,187,240.

T: Very clever thinking! Now can we add these two on the calculator to get the answer?

S: No. We already know that the answer has more than eight digits. So we must add the numbers by hand.

S: I did it. the number is 229,345,007.

T: Good. I wonder what the largest number is that can be put on the display of the calculator. Think about that. And if you press the "3" button and then the "x" button successively, what is the largest number that will show before overload?

The above examples suggest that children can be turned on just as much by intellectual challenges as they are often turned off by performing prescribed tasks to acquire computational speed and skills. These examples exploit what we could call the "languages of strings and arrows", which have wide potential to deal meaningfully with mathematical situations such as those in the following examples.

Students of ages 11 or 12:

An example of the "language of strings":

T: Let's play another numerical string game. (*Draws the string diagram as shown below, and writes the list of possible attributes [unknown to the students] of the two strings as shown below.*

In the many versions of the game, the object is to identify the labels of the strings based on evidence given by dots for numbers placed in the various regions of the diagram.) I've given you some clues as a starter. One clue is the hatching of the region common to the red and blue strings. What does that tell us?

	Red	Blue
multiples of 2		
multiples of 3		
multiples of 4		
multiples of 5		
multiples of 10		
odd numbers		
positive prime numbers		
greater than 50		
less than 50		
greater than -10		
less than -10		
positive divisors of 12		
positive divisors of 18		
positive divisors of 20		
positive divisors of 24		
positive divisors of 27		

S: If a region of the string diagram is hatched, that means that the only numbers in that region are the ones shown. If no dots for numbers are in the a hatched region then there are no numbers there.

T: Good. So that means there are exactly three numbers in both the red and blue strings. Do we know what numbers they are?

S: No. All we know is that there are exactly three of them, because the dots are not labeled.

T: I wonder whether we have enough clues already to tell what labels are on the strings, or whether we need to make some plays to get more clues.

(*Sometimes the game is played between two teams, each having available a set of cards labeled with numbers from which to play alternatively, with the teacher saying "yes" if the card is placed in the proper region and "no" otherwise.*) You can use your analysis sheets to help you decide whether these clues will be enough to identify the strings. (*Each student has a copy of the list of attributes*)

S: We know that "6" is not a multiple of 4, or 5, or 10; so for the Red string we can cross out "multiples of 4, 5, and 10". (*Students do this in the Red column of their analysis sheets with "x"s.*)

S: And Red can't be "odd numbers" or "greater than 50" or "less than -10" or "is a positive divisor of 20 or 27". (*All agree after giving reasons.*)

T: Very good. We crossed out 8 of the labels for Red. Are there others we can eliminate?

S: I have another. Red can't be "positive prime num-

bers”.

S: I don’t see any more for Red. But for the Blue string we can cross out all the “multiples” because -1 is not a multiple of 2 or 3 or 4 or 5 or 10. And we can cross out “positive prime numbers”, “greater than 50”, “less than -10” and all the “positive divisor” labels. (Again the class checks these suggestions and agrees.) But we still don’t know the labels of the strings.

(At this point the students’ analysis sheets look like this.)

	Red	Blue
multiples of 2		x
multiples of 3		x
multiples of 4	x	x
multiples of 5	x	x
multiples of 10	x	x
odd numbers	x	
positive prime numbers	x	x
greater than 50	x	x
less than 50		
greater than -10		
less than -10	x	x
positive divisors of 12		x
positive divisors of 18		x
positive divisors of 20	x	x
positive divisors of 24		x
positive divisors of 27	x	x

T: Have you thought about the fact that both strings have exactly three numbers in common?

S: OK. Let’s suppose Red is for “multiples of 2 or “multiples of 3”. Then those three dots in the middle are for “multiples of 2” or “multiples of 3”. But those three dots are also in Blue, and the only possibilities for Blue are “odd”, “less than 50” and “greater than -10”. But -1 is not a multiple of 2 or 3; so Blue could not be for “odd”. And blue could not be for “less than 50” or “greater than -10” because there are more than exactly three multiples of 2 and of 3 that are less than 50 and greater than -10; so blue can’t be for “multiples of 2” or “multiples of 3”. These are the only possibilities for Blue if Red were for “multiples of 2” or “multiples of 3”. That means we can cross these two off the Red.

S: I have some more. Suppose both strings are for “less than 50”. Then all numbers less than 50 are in the middle region. But there are only three numbers there. So we can’t have *both* strings for “less than

50”. Now suppose Red is for “less than 50” and Blue is for “greater than -10”. Then all the numbers between -10 and 50 are in the middle region. But since there are only three numbers in the middle, this can’t be true. So suppose Red is for “is less than 50” and Blue is for “odd numbers”. But there are more than three odd numbers less than 50. So we must conclude that Red can’t be for “less than 50”.

S: The same argument shows that Red can’t be for “greater than -10”. (The students will repeat the argument and then agree.)

T: Now all that are left for Red are “divisors of 12, or 18, or 24”, and for Blue are “odd numbers”, “less than 50” or “greater than -10”.

Now the students’ analysis sheets look like this:

	Red	Blue
multiples of 2	x	x
multiples of 3	x	x
multiples of 4	x	x
multiples of 5	x	x
multiples of 10	x	x
odd numbers	x	
positive prime numbers	x	x
greater than 50	x	x
less than 50	x	
greater than -10	x	
less than -10	x	x
positive divisors of 12		x
positive divisors of 18		x
positive divisors of 20	x	x
positive divisors of 24		x
positive divisors of 27	x	x

S: We can use the same argument to show that Blue can’t be “less than 50” or “greater than -10”. Suppose Red is for “positive divisors of 12, 18, or 24”, and Blue is for “less than 50”. Then there are more than four positive divisors of each of 12, 18, or 24 that are less than 50. So Blue can’t be “less than 50”, and the same argument can be used to show that Blue can’t be “greater than -10”. Hey, we found the Blue string is “odd numbers”.

T: Who can finish the game?

S: We know that Blue is “odd numbers”. Then the three numbers in the middle are all positive odd divisors of either 12 or 18 or 24. The positive divisors of 12 are 1, 2, 3, 4, 6, 12, with only two odd divisors. The

positive divisors of 18 are 1, 2, 3, 6, 9, 18, with three odd divisors. The positive divisors of 24 are 1, 2, 3, 4, 6, 8, 12, 24, with only two odd divisors. So the Red string is for "positive divisors of 18". (*Loud cheers from the class.*)

Although the depth of thinking involved in the above analysis seems remarkable for students of ages 11 or 12, it must be understood that these students began thinking in this way at ages 6 or 7 by playing simpler string games with attribute blocks. Then they moved on at ages 8 or 9 to string games which extended to three strings and then to string games whose attributes are mathematical relations or mathematical operations. What is most interesting about these games and the other mathematical situations in the program is the enthusiasm and enjoyment that children experience when their intelligence is engaged—and it turns out that very few children are immune to the joys of good thinking.

SOME EXAMPLES OF THE "LANGUAGE OF ARROWS"

Much emphasis is placed on exploiting the power of relational thinking. From the beginning children use arrows from dot to dot to describe the relation of the second object to the first, without relying on the natural language. For example, consider this arrow diagram:

Ages 6 or 7: Suppose the dots are for numbers, the red arrow is for "+5" and the blue arrow is for "-9". What is the relation of the green arrow? (That is, number "a" says to number "b", "you are 5 more than me" and the number "b" says to number "c", "you are 9 less than me"). Then what does the number "a" say to number "c"? (*Ans: Green arrow is for "-4"*)

Ages 7 or 8: Suppose the dots are for people, the red arrow is for "you are my father" and the blue arrow is for "you are my sister". What is the relation of the green arrow? In other words, what would person "a" say to person "c"? (*Ans: you are my aunt, or more precisely, my paternal aunt.*)

Ages 11 or 12: Suppose the dots are for numbers, the red arrow is for " $4x$ " and the blue arrow is for " $\div 5$ ". What is the relation of the green arrow? (For example, suppose "a" is 20; then what is "c"? (16). If "a" is 35, what is "c"? (28) If "a" is 1, what is "c"? (4/5). Etc.)

Comment: The relation denoted by the green arrow in each case is the composite of the relations of the red and blue arrows, in that order. In most situations the composite of the blue followed by the red gives an entirely different relation from the composite of the red followed by the blue, although in this case each order of the composition yields the same relation, namely " $4x/5$ ". In fact, this composite relation precisely defines a fraction. For example, the fraction $4/5$ is the result of applying the composite relation $4x/5$ to the number 1.

Ages 12 or 13: Suppose the dots are for lines in a plane, the red arrow is for "you are parallel to me" and the blue arrow is for "you are perpendicular to me". What is the relation of the green arrow? (In this case, we would have to change the color of the green arrow to blue, since line "a" would say to line "c", "You are perpendicular to me".

Ages 13 or 14: Suppose the dots are for rational numbers other than 0, the red arrow is for "R: you are my reciprocal" and the blue arrow is also a red R arrow. What is the relation of the green arrow? (Here we are forced to change the diagram, because of the convention that each dot is for one and only one object. So the green arrow will be a loop from "a" back to "a", as below.)

Ages 14 or 15: Suppose the students are faced with a situation that requires the solution (s), if any, of the equation

$$1/2(2/(x-1)-1)^2 = 2, \quad x \neq 1$$

From past experience in the program students ordinarily would tackle this equation with an arrow diagram (shown below) but some would need only visualize an arrow diagram to guide them as they apply relations, all of which are functions (i.e., mappings), as follows.

The mapping “-1” takes x to $x-1$; “R” takes $x-1$ to $1/(x-1)$; “ $2x$ ” takes $1/(x-1)$ to $2/(x-1)$; “-1” takes $2/(x-1)$ to $2/(x-1)-1$; the square mapping “S” takes $2/(x-1)-1$ to $(2/(x-1)-1)^2$; finally, the mapping “ $(1/2)x$ ” takes $(2/(x-1)-1)^2$ to $(1/2)(2/(x-1)-1)^2$. Each dot in the diagram denotes a unique object and reminds students of its role: “one object—many names”. In this case the last dot in the diagram is for one number with two names: “ $(1/2)(2/(x-1)-1)^2$ ” and “2”.

Then the return arrows (the converse relations) are drawn, as below. All of these converse relations also

are functions, except for the converse of the square function S, which is two-valued (“ $\sqrt{}$ ” and “ $-\sqrt{}$ ”) only if operating on a number greater than 0, and single-valued (“ $\sqrt{}$ ”) if operating on 0, a fact which the students have discovered in the past. Notice that the converse of “ $(1/2)x$ ” is “ $2x$ ”, which maps 2 to 4, which is greater than 0; then the converse of S is two-valued, and maps 4 to 2 and to -2; etc. The process ends when it is found that if there is a number x satisfying the equation, then possible names for x are $5/3$ or -1, neither of which is 1. Finally, it can be checked that if $x = 5/3$ or -1, then the equation is satisfied.

Notice that here there is no need for any confusing “rules”, such as “doing the same thing to both ‘sides’ of an equation”, etc. Much of mathematics consists of the study and application of the composition of functions; in fact, arrow diagrams are often used by mathematicians when they “doodle with diagrams” as they think about abstract theories, where the dots might even represent functions.

The above examples implicitly define a *pedagogy that assures respect for children by providing for their continued intellectual involvement in the learning process*. It is a pedagogy that emphasizes logical and relational thinking of a kind that applies not only to mathematics but to a whole spectrum of disciplines. Such a pedagogy can improve not only the intellectual climate but also the social climate of schools that employ it. There is another strength of such a program that applies particularly in school populations with special cultural characteristics; namely, it is essentially culture-neutral. There is no inherent advantage in coming to it from the “right side of the tracks” nor from the other side.

In regard to its diagrammatic and intuitive approach, no child enters such a program with special “deprivation” baggage.

As stated at the outset, there does exist a complete K-9 curriculum that meets the *Standards* and from which the above examples of pedagogically rich situations were taken. The K-6 portion is the elementary component of the Comprehensive School Mathematics Program (CSMP), which was developed, tested nationally, evaluated extensively and published from 1969 to 1982 by CEMREL, the regional education laboratory in St. Louis, with NIE funding. From 1982 to the present time the CSMP K-6 materials have been revised and extended to CSMP-MS, the 7th to 9th grade program, by McREL, the regional education laboratory in Aurora, CO. The K-6 portion is available for use and the 7-9 portion is in the process of national pilot testing and available for trial by contacting:

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