What if Less Is Just Less? The Role of Depth over Breadth in the Secondary Mathematics Curriculum

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One of the most challenging Common Principles for mathematics educators in Essential schools to implement is "less is more." We are acutely aware of the role of mathematics performance as a gatekeeper; college entrance and placement exams rely heavily on math scores, and the current emphasis on high-stakes testing makes passing math exams a high school graduation requirement in many states. Once our students get to college, they may find themselves paying for math classes for which they earn no credit; many colleges will not give credit for any math class below college algebra (precalculus).

In addition to these immediate obstacles for our students, problems and challenges facing mathematics education include: low mathematics scores of American students in comparison to students from other industrialized nations, decreased student enrollment in undergraduate and graduate mathematics programs, as well as lack of mathematical competence in today's workforce. Although the need for mathematics within science and technology fields is significant, its role goes beyond career preparation; mathematics reasoning is an indispensable tool for informed participation in a democracy. Information and knowledge of our world is increasingly understood and disseminated through the examination of patterns and trends; consequently, decision-making within our society necessitates the individual's ability to sort through relevant information and synthesize facts that affect a particular issue.

At the secondary school level, the achievement gap in mathematics persists, even though federal and state mandates have increased the number of mathematics course requirements for all students. Research indicates that African American, Latino, and Native American students continue to score lowest on standardized assessments. Few of these students then continue to study mathematics beyond lower level courses in high school. This creates a situation for student populations most at risk and, as stated in the 1989 National Research Council's Report, "No one – not educators, mathematicians, or researchers – knows how to reverse a consistent early pattern of low achievement and failure. Repetition rarely works; more often than not, it simply reinforces previous failure."

Teachers and schools who want the best for their students in this context are rightfully pushing for more mathematics instruction. This may seem to be at odds with "less is more," since the first thing many people assume they must do to live out this principle is to start cutting content – and everything looks too important to omit.

In our practice as math teachers and curriculum designers in several different Coalition schools, we have come to see "less is more" in a different light. Rather than a command to cut back, we see this principle as an invitation to consider the role of mathematics education through a different lens, with the following question guiding our work: "What is essential for students to take away from their high school mathematics education?"

When we begin to design programs around the larger understandings and habits of mind that answer this question, we build mathematics programs with a coherence and vision that feel like "less" to students, as they focus on bigger questions that they investigate in depth. At the same time, that laundry list of content that feels so important to cover still exists, but within a structure that allows students to understand and retain what they have learned.

We focus first on uncovering what it really means to be quantitatively literate. The following characterization expressed by Alan Schoenfeld provides us with a conceptualization of what we want for our students and a starting point for curriculum design and implementation:

"Quantitative literacy is the ability to interpret the vast amounts of quantitative data [one] encounters on a daily basis, and of making balanced judgments on the basis of those interpretations. Quantitatively literate people are flexible thinkers with a broad repertoire of techniques and perspectives for dealing with novel problems and situations. They are analytical, both in thinking issues through themselves and analyzing arguments put forth by others."

This definition is congruent with recent reform efforts that have focused on helping students learn to think like mathematicians within their classroom settings. Mathematics education is no longer skill development through routine tasks; rather, it is an effort to present students with complex situations where there is no set solution, and the process of analysis, or breaking apart a phenomenon to understand its components and their effects on one another, takes precedence. Our goal is to help students become well-versed in mathematical language and proficient in symbolic manipulation so that they internalize the tools of mathematics; in turn, we can provide them with messy problems like those mathematicians encounter, not just the formal structures through which mathematicians present their final results. Our task thus has shifted to one that demands students to take ownership of their learning through the exploration of complex problem situations, while teachers provide necessary guidance for students to develop and access relevant mathematical knowledge.

We have attempted to implement "less is more" in a variety of educational contexts. The schools we have been part of include a pilot school in Boston, New Mission High School (New Mission), a charter school in Fitchburg, North Central Charter Essential School (NCCES), and a charter school in Devens, Francis W. Parker Charter Essential School (Parker). The three schools are members of the Coalition of Essential Schools and were founded as such; although New Mission and Parker share more than ten years of existence, they differ in the population each serves. New Mission is considered an inner-city school, while Parker mostly serves suburban residents. NCCES, the newest of the three schools, is an urban school in its fifth year of operation. Although the challenges due to demographics guided our work in each of the three schools, it is beyond the scope of this article to address these in detail.

The Programs

All three of the programs we describe here have used the Massachusetts state curriculum frameworks to inform the course content. Students in these schools must pass the MCAS, the state math exam, in order to earn a high school diploma, and in the case of the two charter schools, their very existence depends on regular charter renewals that closely examine the students' academic performance.

The educators designing these programs have looked to find connections between topics that have been separate, and integrated them through the use of different unifying concepts, expressed through essential questions that capture the thematic focus of the units. The programs spiral so that students see different concepts several times in increasing depth. And while all teachers in these programs model some important mathematical procedures and techniques through direct instruction and practice, they consistently make space in their courses for deeper explorations. The curriculum in these schools is not just a list of things to know, but demands that students use, explore, play around, discover, make connections, and problem solve.

New Mission High School: Mathematical Elements

The mathematics curriculum framework at New Mission High School (where author Roser Giné taught from 1998 to 2004) evolved from leader- and teacher- created school-wide structures that transcended particular disciplines. School-wide Habits of Mind (perspective, evidence, relevance, reflection, connection, and supposition) along with consistent assessment tools provided the needed support for the mathematics program to take root. Each course was guided by a unique essential question (E.Q.) that reflected mathematical processes that teachers and students valued; although general in nature, these questions provided a map for understandings teachers wanted their students to develop (e.g., 10th grade E.Q.: "How do relationships provide evidence to justify conclusions?") The design of each course included outlines of quantitative skills and relevant topics that would help students respond to the E.Q. Direct instruction, routine problems, and more extensive activities and projects constituted classroom activity, generating the tools students needed to explore three mathematical processes through the school-wide Habits of Mind.

The three processes we deemed essential, mathematical modeling, mathematical proof, and problem solving, gave shape and direction to the larger-scope projects that would be portfolio-eligible. Mathematical modeling guided students in finding explanations for relevant phenomena by simplifying a real-world situation using mathematical representations. Through this work, students tested their ideas, determined limitations of their model, and extracted useful results that could inform the original problem. The language of the school-wide habits played a central role in analyzing their models (e.g., supposition: What might happen if we make a small change in one of the variables?).

The proof strand consisted of providing students opportunities to justify their ideas using formal mathematical language. Although the design of possible ‘proof’ portfolio pieces required more teacher guidance, students learned how to make claims from observed patterns and logically organize information to determine the truth of each claim; students pieced together a valid argument from internalized mathematical knowledge.

Finally, the problem-solving strand complemented the other two as it was more directed than a modeling piece, yet still left room for student creativity and exploration of various approaches. These problems helped students move from pattern recognition and testing particular cases to generalization. The Habits of Mind continued to support student learning, helping students make connections from one problem to another or extend ideas to more complex situations.

North Central Charter Essential School: Learning Levels

The mathematics curriculum structure at NCCES reflected a progression of the work begun at New Mission, with the three mathematical processes described above guiding the framework. Giné, the math team leader from New Mission, brought the framework in use for further development at the young Essential school in Fitchburg. In turn, the mathematics team at NCCES, all new to the school that year, had the opportunity and challenge of implementing this framework while further developing it within a different context. Rather than using Habits of Mind to guide classroom activity and student progress, Learning Levels were written to trace possible learning paths for students during their six-year experience at the school (the school serves grades 7 through 12). The Learning Levels would provide consistent language for teachers designing their courses and eventually for student use in identifying their own meta-cognitive processes. Originally developed by the school leaders, Peter Garbus and Melanie Gallo, and by founding teachers, such a progression was already in existence for all disciplines but needed revision within the area of mathematics.

The math faculty created eight categories of mathematical processes we deemed necessary in attaining quantitative literacy as defined above: visualizing, working with graphs, measuring, estimating, using notation, formulating conjectures, proving, and modeling. These processes were applied in the development of learning tasks based on mathematical modeling, problem solving, and deductive/inductive reasoning. Thus, the three revised curricular elements inherited from New Mission were used to describe actual learning activity, such as class problems, activities, and projects through which students applied concepts and skills at an appropriate learning level. The courses were also designed to help students progress at their own pace in each learning level area. We created five levels of Integrated Math classes with guiding essential questions and course content used as vehicles for development of essential understandings reflected in the learning levels and in the three greater mathematical goals. Although in theory students needed to meet Learning Level 4 expectations in order to graduate, we offered a Statistics course and a Calculus course guided by Learning Level 5 to help students understanding extend further.

Above is a sample of the progression outline for “measuring,” one of our eight learning levels for mathematical reasoning.

Francis W. Parker Charter Essential School: Criteria for Excellence

Authors Diane Kruse and Roser Giné currently teach at Parker. The mathematics curriculum at Parker is embedded in the six-year integrated Math, Science, and Technology program. During the first four years (Divisions 1 and 2), students all experience the same core curriculum in two-hour classes team-taught by a math and science teacher. In the final years of the program (Division 3), students take separate one-hour courses selected from a range of courses that allow them to make some choices based on their future goals. Approximately half of all graduates take calculus each year.

The organizing conceptual framework for Parker’s math program is deceptively simple: as they progress through the Divisions, students indicate their readiness to move from one level to the next by demonstrating increased sophistication in the two areas of Mathematical Problem Solving and Mathematical Communication. Throughout the program, students demonstrate their ability to meet standards in these areas through their performance on messy, open-ended tasks that require creative thinking, application of concepts explored in class, and clear communication of the process involved in solving the problem.

In Division 1, Parker's middle school students tackle regular Challenges of the Week (COWs) that relate to both the math and the science content being explored in class. As problem solvers, students at this level are learning to make connections between the disciplines, and to be persistent when a problem takes more than one day to solve. Classroom activities and instruction are designed to foster a spirit of inquiry, as well as to provide practice with some of the underlying skills and content that students are learning. Over the course of two years, students improve their ability to organize data in several forms and to find patterns and trends in that data that tell a story. They begin using algebra, diagrams and other strategic approaches to organize what they know and figure out what to try next. They start to develop the habit of finding more than a one-solution approach to a problem. The emphasis on communication at this level is primarily on fully explaining the solution process, showing all work, and answering all questions fully and completely. While they are learning some of the conventions for formal mathematical communication (particularly the use of graphs, charts, and tables), students at this level may still be quite wordy in their discussion of a problem, since their thinking is more concrete and the emphasis is on getting all of what is in their heads down on paper.

In Division 2, students formalize their study of algebra and geometry and learn more techniques for data analysis in the context of their science work. Assessments are more varied and may include problems of the week, major projects, and in-class academic prompts. Problem solving in Division 2 demands a greater level of algebraic thinking and abstraction, and students are expected to use multiple approaches to verify their solutions to problems. Mathematical communication becomes more formal as well, as students start paring their wordy discussions into more efficient symbolic explanations, and shift their tone from first to third person. In particular, students develop a deeper understanding of the use of variables, both for problem solving and for effective communication.

By Division 3, students are ready for a great deal of abstraction. They are expected to approach any mathematical problem solving task with a clear and systematic approach, where they frame and organize what they know, make connections to content and techniques that may prove useful, carry out a solution to the problem, then verify their work, sometimes with formal proofs. Communication at this level is highly technical, using all of the conventions of the discipline to be clear, concise, and efficient. Students edit, revise, and proofread their work to ensure the appropriate level of formality.

What does this look like in practice?

Division 2: Disease Unit
The Disease Unit at Parker consists of an eight-week learning experience guided by three essential questions:*

(*Several learning tasks within this unit were developed and used at New Mission and NCCES)

How can we quantify non-constant change?

How can we use mathematical models to gain information about a particular phenomenon?

How can we model the spread of an epidemic? Why is this useful?

The initial generative task was to investigate the interaction between sickle cell anemia and malaria, using a two-week whole class investigation (source: "A Study of Sickle Cell Anemia: A Hands-On Mathematical Investigation," by Rosalie Dance and James Sandefur, 1998; project supported by the National Science Foundation). This class activity introduced students to non-constant change, exposing them to functions beyond linear and forming a bridge into exponential. Students simulated births from a parent population with a given proportion of normal alleles and mutant alleles (sickle cell) in an environment where malaria is a risk; determining conditions were also provided, yielding distinct proportions of sickle cell and malaria survivors.

The initial goal for the class was to find a function that models the situation described using introductory probability theory. Subsequently, students searched for an input value that could maximize the total number of survivors.

We found this activity to be rich with essential mathematical ideas that would exercise students' ability to construct a math model from a realistic situation and would yield many possible natural connections to a Humanities curriculum. Classes at NCCES and at Parker engaged in this work, and students found different entry points given their individual cognitive skills, while coming together through classroom activity. This served the populations of both schools well, as each had heterogeneously grouped classes. Thus, some students who had experience with quadratic functions applied their function notation skills and their algebraic skills to generate the quadratic equation and explore changes in initial conditions, while first-year students used technology to inform their models. All students were able to experience aspects of probability theory and connections to genetic diseases, both topics of study receiving an in-depth focus during the next curricular year.

Through activities, direct instruction, collaborative work, and oral presentations, the rest of the unit facilitated student development of algebraic skills particular to exponential functions while applying modeling processes to different situations. The final part of the unit focused solely on modeling and introduced students to regression and to methods used to determine the predictive value of generated models (i.e., residuals, correlation coefficient, residual plots).

The culminating learning task and assessment was modified from a similar task initially developed at New Mission, with changes implemented at NCCES. This involved modeling the growth of an epidemic, interpolating or extrapolating from the data using best-fit curves, and analyzing error from regression. Finally, students used mathematical language to communicate their findings, either through a structured report or through a news story set in the time of the disease's greatest impact.

The disease unit combined routine problems mixed with directed problem solving to support student exploration of messy problems in more realistic settings. Although the time spent on this unit was significant, students walked away from the experience with a clearer sense of the power and practice of mathematics.

Division 3: Trigonometry and Geodesic Domes

The Geodesic Dome project has become an annual event in Parker's spring semester trigonometry course. After learning the foundations of right triangle trigonometry and connecting that knowledge to the unit circle and the trigonometric functions, students wrap up the semester by examining what happens when we try to apply trigonometric relationships to non-right triangles.

This unit is a critical example of one of the ways that "less is more" plays out in Parker's program. The basic new content of the unit, the Law of Sines and the Law of Cosines, can be derived and demonstrated in a few brief lessons, and with some practice and application problems, students could be finished and on to new content within a week. However, Parker students spend four weeks designing and constructing geodesic domes, working with the essential question: How can we use right triangle and non-right triangle trigonometric techniques to design and construct a geodesic dome?

To build a geodesic dome, the equilateral triangular faces of a tetrahedron, octahedron, or icosahedron are divided into smaller networks and the vertices of that network are "popped out" to make a rounded figure. For example, a 2V network would find the midpoint of each side of the equilateral triangle (dividing it into two sides), and those midpoints would pop out to form a rounded edge. As students conduct this investigation, they learn about the Platonic solids and prove why there are only three different solids that can be built from equilateral triangle faces. They learn that all of the Platonic solids can be circumscribed, and solve the problem of how the radius of the circumscribing sphere relates to the edge length of each solid. They revisit geometric conventions for naming figures in a diagram, and realize the need for careful naming of each part of their diagrams as the figures quickly become complex (students are visualizing multiple cross-sections of the three-dimensional solid as they attempt to "bump out" different parts of the faces to make a dome). And every step of the way, students are repeatedly searching for triangle relationships – right and non-right – that will allow them to carry out the necessary calculations for building their domes.

The challenge of building a dome is deceptively simple, which allows students to really dig in as problem solvers who need to communicate clearly. As teachers, we can then observe in depth our students' ability to respond effectively to a complex, multifaceted task. We have found that this project appeals to students on different levels. Some students are drawn to the problem solving, while others appreciate having physical models in front of them and are motivated to create something interesting or beautiful.

The Dome project has the added benefit of being easy to differentiate. Almost every student at Parker takes trigonometry, including students on special education plans and students who will not take calculus. Students who have a tough time visualizing can build domes with the octahedron as a base, taking advantage of the many familiar right triangles in the form. Students who need more time to complete a project can work with a simpler 2V or 3V network on the triangular face. Students who need a challenge can subdivide the equilateral triangle face into as complex a network as they like (the current record is seven), or work with a more complex design.

Division 3: The Roller Coaster Project

The Roller Coaster Project was implemented at NCCES within the school's first Calculus course and a revised version was used as a first semester Calculus culminating experience at Parker. Both courses, taught through a deductive reasoning approach in which students are exposed to formal proofs when feasible and on occasion are asked to construct their own, were guided by the following essential questions:

1. How can we uncover the concept of 'closeness' using mathematical language?
2. How do we make sense of and quantify non-constant change? What does this allow us to do that we couldn't do without Calculus?
3. What is the connection between definite integrals and the derivative? How is it relevant? ("How is it relevant?" is Parker's school-wide Essential Question for the academic year 2006-2007.)

The project was used to help students refine their understanding of the derivative and its power in optimization problems (source: "Interactive Web-Based Calculus Projects at Hollins University: Area of U.S. States and Roller Coasters", by Julie Clark and Trish Hammer; website: www1.hollins.edu/depts/math/hammer/coaster).

Students used toy coaster models to create their own paths, with the goal of maximizing a determined 'thrill' function based on height of path and angle of steepest descent (for this, both first and second derivatives are applied). The project cited used more sophisticated mathematics technology, yet without access to MAPLE (a highly specialized mathematics software tool), our Calculus classes were nevertheless up to the challenge of creating a coaster and proceeding with analysis of physical models. With encouraged peer collaboration, groups of students were given coaster kits and the freedom to design a chosen coaster path given the limitations inherent in the materials (an extension to this project includes minimization of materials or cost as an additional optimization problem). Different groups had varied levels of success with the physical model; getting to the mathematical concepts underlying the problem proved to be a frustrating process for some and a highly engaging process for others. Students who were more comfortable solving problems with one set solution encountered moments of anxiety that pushed them to learn from the strength of others. Simultaneously, those who preferred active learning tasks were challenged to formalize their processes using mathematics by tapping their peers' expertise. Multi-directional learning relationships evolved within a small space saturated with toys.

Creative use of technology also emerged from the collaborative work. The project assignment spawned purposeful use of TI graphing calculators and Geometer's Sketchpad. For instance, some groups uploaded digital photos of their toy coasters and used regression to model the paths. Subsequently, calculus was used in the analysis.

This project asked students to apply the ideas learned through class work, homework, and other learning tasks to a problem that depended on flexible application of the mathematical processes embedded within a first-semester Calculus course. Three weeks at the end of the semester were dedicated to this work, as students constructed their coasters, used technology to find best-fit curves, and applied differentiation techniques to optimize a function. Our sense and experience is that within a more traditional Calculus course, students would have moved faster with the material, leaving review time at the end of the year for an end-of-year exam or for the Advanced Placement test. Although both approaches are indispensable with respect to particular course goals, a project of this scope is valuable because it teaches students how to apply what they've learned in a relatively authentic way, and because it broadens classroom activity. Students take ownership of the work, seeing first-hand that people learn in different ways and most important, experimenting and persevering in a safe environment. NCCES students as well as Parker students are still given the opportunity to take the Advanced Placement test for possible college credit; test preparation is then given additional time, either during school hours, or after school.

Conclusion

In Essential schools, teachers walk a fine line as they attempt to be true to the principle "less is more" within their mathematics programs while ensuring that students are quantitatively literate and prepared for both informed participation in our society and careers within science or mathematical fields. We have found ways to do "less" by organizing content around essential questions, and articulating goals for mathematics instruction that transcend the particular content being studied and instead reflect broader skills and mathematical ways of thinking. This is not without its costs; we know that an observer in our classrooms might see fewer exercise sets and fewer course choices, as well. We worry that our students are less facile with algebraic manipulation and that some routine procedures are less automatic than we would like, and we continue to work on building these component skills into the programs of study we design. It is incumbent upon us to ensure that students obtain needed support in internalizing such routines so that they can become more flexible in concept learning and application. However, students in these programs experience the same critical mathematics content as their peers in traditional math programs, and we would argue that they experience this content in ways that engages them deeply and allows them to make more of their mathematics experience.

The kinds of mathematical processes that we have observed in development within our students, along with student products from performance assessments such as the ones described here corroborate our belief that through our programs students are:

1. Transferring mathematical skills and knowledge to non-routine problem situations
2. Developing a meta-cognitive awareness that allows for conscious access of relevant information
3. Internalizing the process of justification
4. Using the language of mathematics to communicate and build upon their ideas.

Although the current standards-based initiative poses a challenge, particularly within schools that have an urgent need to raise test scores, it also provides us with an opportunity to analyze the work we are doing and justify it as we remain accountable to our students.

Testimonials

One year after mathematics coursework at North Central Charter Essential School, structured as described above, students were asked to share their ideas around the principle, "less is more." Some of their responses:

"Rather than just knowing what to move around, or what to plug into where, looking deeper into a topic helped me understand, and I still remember how things worked and why. An example would be the parabola project I worked on with Nick and Kendall, actually making a parabola, and seeing how it should work made the whole concept very clear to understand." -Meaghan Morrissey, current student

"I still find myself remembering the things we covered over the past two years…because of how long we spent on the topics and the projects we did on them." -Chris Foster, current student

"The concept of "less is more" helps me understand a concept, because it allows for more time to study a topic and understand exactly why what happens works. This knowledge in turn made it easier to learn later concepts and processes, for if you know a prior yet related concept the newer one is understood that much easier." -Durrand Michalewicz, current student

Calculus at NCCES "made my calculus class here that much easier, the first part of the course was pretty easy anyway, but once we started getting into real calculus it seemed much more of a review than I thought it was going to be. I realized we'd covered more with you than I'd thought...especially since my roommate was in calc 2 and I'd seen some of what they were doing…I think the best thing about your math class was that it was more traditional than I'd seen before at charter schools (Parker and NCCES) but still non-traditional enough to incorporate the essential school philosophy and allow us to do fun activities/generally have fun." -Kristin Harrington, student at St. Lawrence University

"The calculus class really prepared me for college. I tested out of calculus one at MCLA, it's crazy! And the roller coaster project was really visual, which helped a lot." -Meghan Ekwall, student at Massachusetts College of Liberal Arts

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Parker School Criteria for Excellence Problem-Solving

- You understand the problem.
- You identify special factors that influence your approach before you start.
- Your approach is efficient or sophisticated.
- You clearly explain the reasons for your decisions along the way.
- You solve the problem and make a general rule about the solution.
- You extend what you find to a more complicated situation.

Communication

- You use appropriate mathematical language to communicate your solution.
- You use graphs, tables, charts, and/or drawings to communicate your solution.
- Your work is well organized and detailed.

Several learning tasks within this unit were developed and used at New Mission and NCCES

Do I / Does the Student…

Level 1

- Actively explore how one, two, and three dimensional shapes interact (e.g., investigate volume by fitting contents of one object into others; submerge irregularly shaped objects in water and measure displacement)
- Understand relative size: compare lengths, areas, and volumes
- Use appropriate units in respective dimensions

Level 2
Same as Level 1 and:

- Understand inherent relationships within the same object (e.g., Pythagorean Theorem for right triangles)
- Understand relationships among properties of objects (e.g., discover how many cones fit within a cylinder with the same height and base)
- Measure angles

Level 3
Same as Level 2 and:

- Represent measurements of objects using equations
- Solve problems and explore applications using formal equations
- Measure unknown quantities indirectly (e.g., using triangles & similarity)
- Apply understanding of length, area, volume, etc. to real-world problems
- Use significant digits when calculating error in measurement

Level 4
Same as Level 3 and:

- Justify mathematical expressions of measurement (e.g., formulas for volume of cone, area of triangle)
- Measure indirectly (e.g., using trigonometry)

Level 5
Same as Level 4 and:

- Make a conjecture based on observations and use a logical argument to prove it

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Related Resource

For more from Roser Giné on her work at New Mission High School, read “What Is Essential in a High School Mathematics Curriculum Framework?” from Horace Volume 20, Issue 2, Winter 2004.

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