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ABSTRACT

The National Council of Teachers of Mathematics and the Center for Mathematics Education of the University of Maryland sponsored a conference to consider the impact of computing on school mathematics. Participants (including mathematics teacher educators, mathematicians, computer scientists, elementary and secondary mathematics teachers, and others) were asked to respond to a series of questions related to the impact of computing technology on the mathematics curriculum, mathematics instruction, and mathematics teacher education, and to formulate general recommendations in each of these areas. These recommendations (or proposals) are presented in this document. They are intended as guidelines for selecting the content of precollege mathematics curricula, for teaching that content in a manner that takes advantage of emerging technology, and for designing teacher education programs that recognize the changing curricular patterns and instructional roles for teachers. Five fundamental assumptions upon which these proposals are based are listed. One of the recommendations offered is that pre- and in-service programs include components which focus on computer awareness, interaction with prepared software, and interaction with programming. (JN)

NATIONAL COUNCIL OF TEACHERS OF MATHEMATICS

THE IMPACT OF COMPUTING TECHNOLOGY ON SCHOOL MATHEMATICS

REPORT OF AN NCTM CONFERENCE

One of the critical problems facing mathematics education today is the need for curricula and instructional methods to respond to the influence that computing technology is having on mathematics and its teaching. Numerous conferences, reports, and projects have focused on different aspects of the effect of emerging technology on mathematics curricula and instruction. For example, the Conference Board of the Mathematical Sciences produced a set of guidelines that identified fundamental topics in K–12 mathematics (CBMS 1983), and an NSF-sponsored conference at the University of Maryland resulted in a document that provided insight into the effect of the computer on subjects in the traditional secondary mathematics curriculum (Fey 1984).

NCTM has made many efforts to provide leadership as decisions about the impact of computing technology on mathematics education are made. In 1981 its Board of Directors established the Technology Advisory Committee, which has subsequently engaged in several projects and activities that serve members in the area of technology and which advises the Board on matters relating to technology and mathematics education. NCTM sponsors a continuing series of seminars for K–12 mathematics teachers on the uses of computers in mathematics instruction and has for a long time devoted program slots at regional and national meetings to issues associated with the impact of technology on mathematics education. The publications of NCTM, including the journals and the 1984 Yearbook, reflect the continuing concern of the organization with this issue.

In an effort to continue its leadership role, NCTM and the Center for Mathematics Education of the University of Maryland, with financial support provided by the National Science Foundation, sponsored a conference at NCTM headquarters during March 1984 to consider "The Impact of Computing on School Mathematics." Participants represented a number of interested constituencies: government funding agencies, commercial publishers of mathematics materials, the standardized testing industry, mathematics teacher educators, mathematicians, computer scientists, elementary, middle, and secondary mathematics teachers, and district-and state-level mathematics supervisors. Participants were asked to respond to a series of questions related to the impact of computing technology on the mathematics curriculum, mathematics instruction, and mathematics teacher education, and to formulate general recommendations in each of these areas. The conference produced the recommendations herein—each gaining broad, if not unanimous, support.

RECOMMENDATIONS ON CURRICULUM, INSTRUCTION, AND TEACHER EDUCATION

Prologue

Applications of calculators, computers, and other electronic information technology are reshaping the fundamental methods of doing and teaching mathematics. When used as tools for arithmetic and for the analysis of graphic or symbolic data, calculators and computers offer powerful new approaches to familiar problems and access to entirely new branches of mathematics. Applications of these same capabilities to instruction are bringing major changes to mathematics classrooms and the roles of mathematics teachers.

The major influence of technology on mathematics education is its potential to shift the focus of instruction from an emphasis on manipulative skills to an emphasis on developing concepts, relationships, structures, and problem-solving skills. Traditional precollege mathematics curricula have stressed the development of a variety of mechanical procedures, including the computational algorithms of arithmetic and the transformation of symbolic expressions in algebra, trigonometry, and analysis. The use of calculators and computers as standard tools in quantitative problem-solving situations, however, has diminished the value of human proficiency in the execution of such procedures. Much of the instructional time currently devoted to acquiring proficiency with paper-and-pencil algorithms should be reallocated to support a range of new or previously neglected topics that have a valid place in the K–12 mathematics curriculum. Moreover, teacher education programs must be modified to reflect these changes in school mathematics content and to model the delivery of instruction through appropriate applications of technology.

The proposals that follow are intended as guidelines for selecting the content of precollege mathematics curricula, for teaching that content in a manner that takes advantage of emerging technology, and for designing teacher education programs that recognize the changing curricular patterns and instructional roles for teachers. The proposals are based on five fundamental assumptions:

1. Coordinated change can take place simultaneously at all levels of mathematics instruction.
2. All students and teachers will have access to calculators and computers for the study of mathematics, in the classroom and at home.
3. All students will experience appropriate application of computers in the study of each school discipline.
4. State/provincial, district, and local mathematics curriculum guidelines and criteria for mathematics textbook adoption will be rewritten to reflect the changing priorities of school mathematics.

5. The publishers of standardized tests and instructional materials will
   (a) immediately begin developing products that are consistent with the changing objectives of precollege mathematics;
   (b) continue support for that development on a schedule that facilitates the implementation of proposed curricular changes.

TECHNOLOGY AND THE MATHEMATICS CURRICULUM

Today, the computational skills of arithmetic, algebra, geometry, trigonometry, and calculus dominate the K–12 mathematics curriculum. The content and sequences of courses are planned carefully so that students acquire intricate hierarchies of prerequisite skills for each major computational algorithm. Although these well-known mathematical procedures originated as essential aids to efficient problem solving, most of the algorithms of school mathematics have now been programmed for rapid execution by calculators and computers.

To do arithmetic today, mental operations are best for obtaining quick approximations; calculators are the tools of choice for one-time computations; and computers are most appropriate for repetitive calculations. In algebra, trigonometry, and calculus, computers can execute the numerical and symbolic manipulative procedures that students spend countless hours mastering.

As a consequence of this changing environment for mathematical work, the curriculum in grades K–12 needs careful reassessment and revision. Classroom teachers, mathematics supervisors, members of state departments/provincial ministries of education, authors and publishers of textbooks, developers of standardized tests, and other curriculum developers must consider the following recommendations and the questions they raise.

Elementary School Level

The elementary school mathematics curriculum has traditionally focused on developing students' skills in computing with whole numbers, fractions, decimals, and percents. Since computers and calculators can perform such operations more quickly and accurately than can usually be done otherwise, the traditional goals of elementary school mathematics must be reexamined and the predominance of computation-related objectives must be reassessed. Curriculum developers are urged to consider the following recommendations that suggest a broadened view of mathematics appropriate for grades K–4.

* Calculators should routinely be available to students in all activities associated with mathematics learning, including testing. Students should be taught to distinguish situations in which calculators are appropriate aids to computation from situations in which mental operations or paper-and-pencil computations are more appropriate.
* Emphasis should continue to be placed on students' knowledge of basic facts required for proficient mental arithmetic and estimation. However, significant portions of elementary curricula devoted to algorithms for multiple-digit calculations can be eliminated.
* Instruction must shift to emphasize the meaning of arithmetic operations. Such understanding is essential for problem solving.
* Experience with physical manipulatives and other concrete representations of concepts must continue to be an important phase of learning mathematical ideas. Because of the increased instructional emphasis on meaning and understanding, this activity must not be overlooked as the curriculum evolves to take advantage of computers and calculators for instruction.
* Because computers and calculators can be used effectively in teaching mathematical concepts, no a priori assumptions should be made about the appropriateness of any given mathematical topic for elementary students. For instance, decimals, negative numbers, and scientific notation appear naturally when using calculators and can be taught as they arise. Computers facilitate an early introduction to geometric concepts such as transformations, congruence, and vectors; statistical concepts such as randomness; and algebraic concepts such as variable and function.
* Preprogramming activities and simple computer programming in Logo or BASIC can be done by students as early as the kindergarten level to convey both mathematical and computer concepts. Computer literacy should come as a natural by-product of such experiences rather than as a special addition to the elementary school curriculum.

Middle School Level

The mathematics curriculum for the middle school (grades 5–8) must take into account incoming students' knowledge of new topics such as computing, their understanding of topics formerly reserved for the middle grades, and their more limited skills in topics such as arithmetic algorithms. In addition to building on the changes proposed for the elementary grades, curriculum developers for the middle grades should consider the following specific recommendations.

* Mathematics in the middle grades should emphasize the development of "number sense"—the intuitive feeling for the relative sizes of numbers that is essential in skillful estimation, approximation, mental arithmetic, and the interpretation of results for reasonableness.
* Some portion of instructional time should be given to the study of discrete mathematics, including counting, graph theory, probability, and logic, which is important and appropriate for the middle grades.
* Calculators and computers can be used to teach iterative procedures for solving significant problems before traditional formal methods are presented. Such experiences should be part of the middle school mathematics curriculum.
* An introduction to statistics should include extensive gathering, organization, and presentation of data. Important concepts can be developed in the context of real data sets whose manipulation and examination is aided by computer analysis and graphing software.

- Middle school mathematics programs should take advantage of the visual display capabilities of computer graphics that support and underscore the importance of informal geometry objectives. Transformations, mensuration formulas, and spatial visualization can be vividly illustrated by using computer graphics.
- Increased emphasis should be placed on such nontraditional methods of problem solving as organized lists, guess and check, geometrical sketches, and successive approximations, all of which are made feasible by calculators and computers.
- Computer programming experiences that introduce the concepts of variable and function should be provided. These experiences should help prepare students for the study of algebra.
- By the end of grade 6, students should be able to write simple computer programs that require looping and branching concepts. The emphasis in such programming activities should be on problems that convey significant mathematical ideas.

Senior High School Level

Developers of senior high school mathematics curricula must consider both the changing preparation of their entering students and the changing college and work environments their graduates will enter. The following recommendations are suggested as guidelines for the curricular evolution that must occur if high school mathematics programs are to reflect appropriately the influence of technology on mathematics and its teaching.

- The selection and sequencing of high school mathematics for college-bound students should no longer be governed solely by preparation for calculus. The most important mathematics for many students will consist of topics from discrete mathematics and statistics. High school programs must reflect these goals in their content and priorities.
- Computing is changing calculus and its traditional prerequisite subjects. Computer symbolic systems, graphics, and numerical analysis software make student mastery of manipulative procedures less important and, at the same time, offer dynamic tools for the illustration of fundamental concepts and processes. Such changes should be considered as the influence of calculus on high school mathematics is assessed.
- The content priorities and approaches to topics in high school geometry should be reconsidered in light of computer graphics and their applications. The geometry of three-dimensional space, trigonometry, vectors, coordinates, and transformations are all made more accessible with computer assistance through visual displays and complex calculations.
- The skill-objectives of algebra must be reassessed to identify those procedures more easily done by computer (e.g., combination of expressions or solution of equations) or calculator (e.g., values of trigonometric functions, logarithms, or exponentials). The properties of elementary functions are still important for modeling quantitative relationships, but proficiency in many familiar computational processes is of little value.
- In many topics of high school mathematics, computers and calculators can be used to discover and test principles and methods. For example, concepts and theorems can be illustrated numerically and graphically to develop sound understanding before formal proof is attempted.
- For high school students with limited ability or interest in mathematics, technology offers an opportunity to enrich curricula with realistic problem-solving situations without insisting on a mastery of skill prerequisites. For example, these students can concentrate on the skills needed to collect, organize, and interpret mathematical information, skills appropriate for estimation and approximation, problem-solving strategies, data analysis methods, and reasoned evaluation of results.

The time needed for new curricula will probably exceed the time that can be saved by reduced emphasis on topics of diminished importance or by a more efficient organization of instruction. Mathematics is of such fundamental importance, however, that schools must allocate more time to its study. This means more minutes per day in the elementary and middle grades and more years of mathematics in secondary school.

TECHNOLOGY AND MATHEMATICS INSTRUCTION

The impressive capabilities of emerging technologies promise major changes in the organization of mathematics instruction and in the roles of students and teachers. Computers offer a dynamic electronic chalkboard for the demonstration of mathematical ideas. As laboratory tools, they assist in the exploration and discovery of concepts, the practice of skills, applied problem solving, and instruction by simulation. Computer-based evaluation and information management provide further opportunities for change in traditional teaching/learning patterns.

Although there may be risks associated with changing instructional patterns and teachers' and students' roles, the potential for improved instruction in mathematics makes the search for ways to reduce those risks worthwhile. If teachers and students are to exploit the potential of technology to support instruction, they must become adept at the new roles described in the recommendations below.

One of the most immediate consequences of the integration of technology into mathematics instruction is the increased need for teachers to make informed decisions about questions that relate to certain aspects of the mathematics curriculum. The following recommendations focus on these issues.

- Teachers must be able to make informed curricular decisions about the appropriate place and strategy for using technology to enhance instruction.
- Teachers must learn how dynamic visual displays made possible by computers can aid transition from concrete experience to abstract mathematical ideas.
- Teachers must become adept at interpreting and elaborating computer-based evaluation of student learning and in using information management systems that organize curriculum options and assessment data.

New roles for classroom teachers and students are also made possible by technological enhancements of mathematics instruction. Among these roles are the following:

- Teachers must become effective catalysts for student-directed learning. They must be able to pose stimulating problems and to probe student understanding with questions that begin "What would happen if . . .?"
- Teachers must serve as learning models in attacking mathematical questions. They must be comfortable assisting students in learning situations in which the topic being studied or the resource employed is unfamiliar. Teachers must be prepared to say, "I don't know yet," while they join students in exploration.
- Teachers must become facilitators of cooperative learning as students engage in realistic learning projects that computers make attractive. Teachers and students must emulate real problem solvers as they deal with problems of complexity, accuracy, and precision that occur in the collection and analysis of real data.
- For students, the greatest promise and challenge of technology in mathematics learning is the move toward more self-directed and self-monitored learning. Students must become adept at using computer-based instructional materials, mathematical tool software, and personal programming skills to develop and practice the use of mathematical concepts, principles, and problem-solving processes.
- Student-directed learning suggests that students may become dispersed throughout the learning environment. Teachers must know how to maintain effective communication with and among learners and must recognize that individualized technology-enhanced learning is not synonymous with independent study.

The fundamental theme that underlies recommended changes in patterns of mathematics instruction and in the roles of teachers and students is the emergence of a new relationship among teachers, students, and the subject matter. The presence of computers and calculators in demonstration, practice, problem solving, and evaluation creates a new classroom dynamic in which teachers and students are natural partners in the search for an understanding of mathematical ideas and a solution of mathematical problems.

TECHNOLOGY AND MATHEMATICS TEACHER EDUCATION

The recommendations in previous sections of this report suggest a new look to mathematics classrooms, with concepts and problem solving the focus of curricula and teachers joining their students as active partners in learning. If these changes are to occur, classroom teachers must be the primary agents of change. Consequently, preservice and in-service mathematics teacher education programs must be restructured to prepare teachers for their new roles.

Computer education for teachers of mathematics requires understanding and skill in three areas: (1) the uses of computers and calculators as problem-solving tools in mathematics; (2) the uses of computers for the presentation, evaluation, and management of instruction; and (3) the concepts of computer literacy that contribute to, or depend on, the knowledge of mathematics. The breadth and depth of appropriate computer education will vary with the teacher's grade level and subject specialization. The following recommendations provide guidelines to the content and form of preservice and in-service experiences suitable for elementary, middle, and senior high school mathematics teachers.

Mathematics content and methods courses in teacher education programs must be examined and restructured to give more attention to priority content areas and to make calculator and computer use an integral part of all such courses. In particular, the following recommendations apply:

- Students preparing to teach at the elementary level must complete the mathematics requirements outlined in the *Guidelines for the Preparation of Teachers of Mathematics* (NCTM 1981), with special emphasis on estimation, approximation, mental arithmetic, data organization and analysis, informal geometry (using a variety of approaches to the subject that reflect its visual nature such as transformations, vectors, and coordinates), probability concepts, and measurement concepts.
- Computer literacy and programming concepts needed by elementary teachers should be acquired through experience in the mathematics content and methods courses. Consequently, teachers preparing to teach at this level need not be required to take a formal computer science course, although a course focusing on computer applications in education is recommended.
- Students preparing to teach at the middle school level should also complete the mathematical requirements outlined in the NCTM *Guidelines* for this level, with special attention to the priority topics recommended for elementary teachers and experience with more advanced topics from algebra, analysis, statistics, and discrete mathematics.
- Middle school mathematics teachers should complete a course on computer applications in education and a computer science course that focuses on problem solving and, more specifically, on the nature of algorithmic thinking and the computer implementation of problem solutions.
- Students preparing to teach mathematics at the secondary level should complete the mathematics major outlined in the NCTM *Guidelines* and coursework in discrete mathematics, probability and statistics (including exploratory data analysis), and numerical analysis. All topics must be taught in ways that demonstrate appropriate applications of computing to mathematics.
- In addition to the computing courses recommended for middle school teachers, secondary mathematics teachers should complete study that provides further experience with structured programming, algorithmic thinking, mathematical modeling, and other mathematics fundamental to computer science.

To provide teachers of mathematics with the knowledge and skills needed to use computers and other technology effectively for instruction, programs of preservice and in-service education must include the following components:

- Level 1 (awareness). Through the use of computers, calculators, and other technology as an integral part of the delivery of instruction in mathematics, teachers must be exposed to a variety of applications that enhance their understanding of the potential of these technologies. They must experience a range of hands-on activities and explorations and see demonstrations of appropriate uses of technology in classrooms.

- Level 2 (interaction with prepared software). Teachers at this level must be given training in the selection and use of appropriate software to enhance instruction in mathematics, and information should be given to them about sources of mathematics-related software. They must develop, deliver, and evaluate lessons and units that integrate existing software into mathematics instruction.
- Level 3 (interaction with programming). Teachers should be given the opportunity to engage in programming-related activities such as tracing, debugging, or modifying existing programs, all of which can enhance mathematics learning. Such experiences should focus on how programming ideas can be used to teach mathematical concepts, not on developing the teacher's personal programming skills.

The most important point in these recommendations for change in mathematics teacher education is the requirement that preservice and in-service programs must model the desired changes. Teachers must *experience* mathematics content and methods courses that emphasize priority topics and that present those topics using a variety of techniques that fully integrate computers, calculators, and other information-processing technologies. The realization of this goal will require commitment and cooperation among mathematics and teacher education faculties. Institutions must commit needed resources for equipment and must support faculty study time.

- Every institution should identify a computer resource teacher who can serve as a technical advisor for all teachers and a mathematics/computer resource teacher who can provide leadership in helping teachers make appropriate use of computing devices in mathematics instruction. Institutional support for training such individuals will be needed.
- Institutions must provide ongoing support mechanisms. Administrators must be educated about proposed changes in mathematics content and the delivery of instruction and must be supportive of changes. Initiative and achievement must be recognized.
- Colleges and universities should work with local schools and districts to devise creative models for in-service programs to upgrade teachers' backgrounds and ways to provide support for teachers as changes are implemented. Such programs must build in mechanisms to inform teachers at upper levels about curricular and instructional changes at lower levels and vice versa.
- Professional organizations such as NCTM must offer training workshops to prepare teacher educators for leadership roles in effecting change. Funding agencies must offer support for retraining activities.

Well-educated, committed teachers will be the key to the successful implementation of curricular and instructional improvements. The computer education of preservice and in-service teachers represents a critical investment necessary for change to occur.

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