How Mathematics Education in Ohio Impacted the Nation: Incorporating Technology to Carry Out the Vision

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Abstract

This invited article explores the historical contributions of technology to mathematics education, focusing on the pioneering work of Bert Waits and Frank Demana. From early experiments with closed-circuit television and calculators to the development of function graphing technology, their innovations have transformed the way students learn algebra. The paper highlights key milestones in their journey and reflects on personal anecdotes that showcase the profound impact of technology on teaching and learning in mathematics.

Keywords: Mathematics Education, Function Graphing, Bert Waits, Frank Demana, Graphing Calculators, Technology in Education

The Ohio State University, A Pioneer in Technology

Technology played a prominent role at OSU since the late 1960s. Closed circuit television was utilized to deliver mathematics lectures, and prototype Texas Instrument four-function calculators were used by students in pre-calculus courses. OSU mathematics education professor Marilyn Suydam created and directed an international Calculator Information Center (Schultz, 2024). Some of the first computer animation was done at OSU in 1967 by department of art professor Chuck Csuri, who created an animated hummingbird, purchased by the Metropolitan Museum of Modern Art in 1968 as representative of one of the world's first computer animated artworks. Bert Waits, John Riner, and I were amazed to see Csuri's hummingbird and another animation, which travelled within the human body. Though animation is commonplace today in giant jumbotrons, we had never imagined anything like it at the time! The transformations of the hummingbird may have been an inspiration for Waits' interest in the use of computer graphics to teach mathematics.

Figure 1: Csuri Hummingbird (Csuri, 1967).

This article will examine Bert Waits' early history with technology, his key role in the creation of function graphing technology; his partnership with Frank Demana, which took function graphing to the international level; and, examples of how function graphing technology led to new approaches to teaching algebra and statistics.

Bert Waits' Early History of Using Technology Leads to the Creation of Function Graphing Technology

Bert Waits' publications provide a chronology of the use of technology in the teaching of mathematics. To aid in recognizing the milestones, they are highlighted in **bold font**. Always at the frontier, Waits' interest in technology began with his 1967 dissertation research comparing university mathematics classes using **closed-circuit television** lectures with traditional lectures, subsequently published in *Educational Studies in Mathematics* (Waits, 1970), his first journal publication. He published another journal article about the role of television in mathematics instruction in what was then called *The Two-Year College Mathematics Journal* (TYCMJ) (Waits, 1974), this time about the use of **videocassettes**, which were being used in OSU mathematics courses.

He published his first article about the use of **four-function calculators** in college-level mathematics remedial courses with Joan Leitzel in the *American Mathematical Monthly* (Leitzel & Waits, 1976), and two more articles on his own in the *TYCMJ* (Waits, 1978a) and the *Mathematics Teacher* (Waits, 1978b). He co-authored an article about the use of **programmable calculators** as a teaching machine with Patricia E. Hallden-Abberton, then a System Analyst for Unisys (Hallden-Abberton & Waits, 1978), and coauthored two articles about the use of **scientific calculators** in solving problems by iteration in the *Mathematics Teacher* (Waits & Schultz, 1979b) and the *TYCMJ* (Waits & Schultz, 1979a).

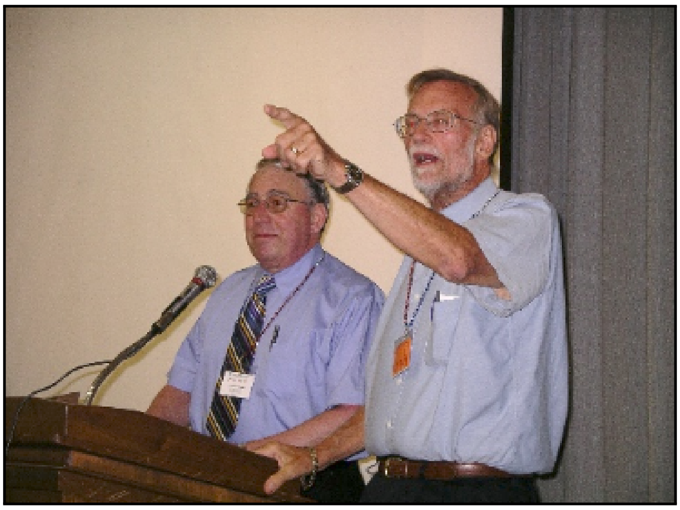
What is remarkable about Waits' connection to **function graphing technology**, is that while he was a pioneer in the use of closed-circuit television, videocassettes, four-function calculators, programmable calculators, and scientific calculators in teaching mathematics, he was a principal developer of function graphing technology. I have a special memory of his "aha" moment when he first succeeded in creating the graph of a function on an oscilloscope connected to a computer in his office. I was across the hall when he called me over to share in his excitement. It was clear even then that he realized the classroom potential for his innovation in the teaching of college pre-calculus mathematics.

Bert Waits' and Frank Demana's Development of Function Graphing Technology

While Waits collaborated with Joan Leitzel and co-authored two articles with me regarding using calculators in teaching mathematics, Frank Demana worked with State of Ohio Supervisor Margaret Comstock (Comstock & Demana, 1987) and OSU mathematics education professor Alan Osborne (Demana & Osborne, 1988). Because Demana was actively involved with secondary schools, it is likely he who saw its potential there.

Bert and Frank formed their signature partnership featuring collaboration between a mathematics educator and a mathematician. Perhaps surprisingly, it was Waits, *the mathematics educator, who used his knowledge of mathematics to develop the function grapher for use at OSU, while it was Demana, the mathematician, who was the force behind its use in secondary schools.* Regardless, it was their collaboration that overshadowed their individual professional statuses.

Figure 2: Frank Demana and Bert Waits at USACAS in 2004 (photo by Jim Schultz).



Their publications indicate that function graphing technology had been incorporated into computer displays by 1987. In their first coauthored article, "Problem Solving Using Microcomputers," published in *The College Mathematics Journal* (Demana & Waits, 1987), they maintained that "microcomputers technology has evolved to the stage it should be routinely used by mathematics students at all levels." Subsequent articles explained how to program an Apple II computer to create graphs with the proper coordinates (Demana & Waits, 1988a) and made the claim that "microcomputers and **graphing calculators** have evolved to a stage where they should be used by students at all levels" (Demana & Waits, 1988b).

Though CASIO had marketed the first graphing calculator in 1985, Waits and Demana extended OSU's relationship with Texas Instruments, which began with the early use of TI's prototype four-function calculators in OSU precalculus classes in the 1970s. According to ERIC, Waits and Demana went on to publish over a dozen articles mostly about the use of graphing calculators. Somewhat unexpectedly, their first article about **computer algebra systems** discouraged their use (Waits & Demana, 1992). With substantial support from Texas Instruments, Waits' and Demana's efforts were a major factor in the worldwide use of graphing calculators.

Function Graphing Technology Fosters a New Approach to Teaching Algebra

Waits and Demana described the role of graphing calculators in mathematics reform in an essay of the same name (Waits & Demana, 1998), reprinted in part on the next page.

The essay pointed out that the 1989 NCTM *Standards* assumed that graphing calculators would be available to all students at appropriate times. This is not unexpected, since Waits was one of the authors of the *Standards*. Waits and Demana also stressed the importance of a balanced approach, with paper-and-pencil computation and technology representations informing and reinforcing each other, and the idea of a teacher support network.

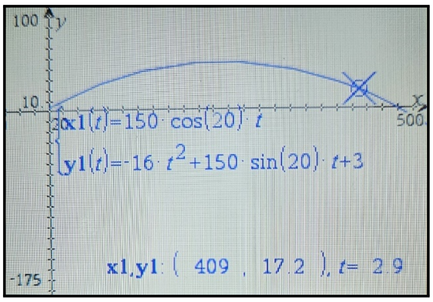
Gail Burrill and others have posited that while functions are one of four essential aspects of algebra, modeling, language or representation, and structure are also important—moreover, that no one theme in itself is sufficient to give students a complete picture of what it means to know and be able to do algebra (Burrill, 1995). The idea that no one approach is sufficient to learning algebra also resonates with Joe Crosswhite's remarks cited in the first article (Schultz, 2024), urging for balance between different approaches in the teaching of mathematics, a view also affirmed by Waits and Demana.

> What did we do in our graphing calculator projects that were different from past practices? It is important to note that the mathematics content of our projects was easily recognizable. We did not "replace" traditional mathematics content. We used "power of (graphing calculator) visualizations" to do many "new things" itemized as follows.
>
> 1. Approach and solve problems numerically using tables, etc. on graphing calculators.
> 2. Graphically SUPPORT the results of applying algebraic paper and pencil manipulations to solve equations and inequalities.
> 3. Solve equations and inequalities using graphing calculators and then CONFIRM the results using analytic algebraic paper and pencil methods.
> 4. Model, simulate, and solve problem situations using graphing calculators and then confirm, when possible, using analytic algebraic paper and pencil methods.
> 5. Use graphing calculator generated scenarios to illustrate mathematical concepts.
> 6. Use graphing calculator methods to solve equations and inequalities that cannot be solved using analytic or algebraic methods.
> 7. Conduct mathematical experiments assisted by graphing calculators to make and test conjectures.
> 8. Use graphing calculators to study and classify the behavior of different classes of functions.
> 9. Use graphing calculators to foreshadow concepts that will be encountered in later courses (to build intuition).
> 10. Use graphing calculators to investigate and explore the various connections among different representations of a problem situation.
>
> When graphing calculators are being used, we have found that students are actively involved in problem solving and talk and read about the mathematics they are learning. We revisit important problem situations so that students can anchor new ideas in familiar contexts. Also, student learning is facilitated by encountering many instances on which to make generalizations (Waits & Demana, 1998, p. 3).

On a personal note, my understanding of several topics from the traditional mathematics curriculum was significantly enhanced when I was exposed to graphing calculator technology. In particular, I had never encountered parametric functions in any meaningful way, yet with examples like the flight of a baseball, I found parametric functions to be one of the most engaging aspects of graphing calculator technology. In the modified textbook example shown in Figure 3 (Demana & Waits, 1990), students are asked to use graphing technology to determine whether a baseball hit from a height of 3 feet at an initial velocity of 150 feet per second at an angle of elevation of 20° would clear a 15-foot-high fence 400 feet away. As Figure 3 illustrates, the trace feature shows that at 2.9 seconds the ball is at a height of 17.219 feet after traveling over 400 feet, so it would clear the fence. It is difficult to envision students actively involved in solving this real-world problem without function graphing technology.

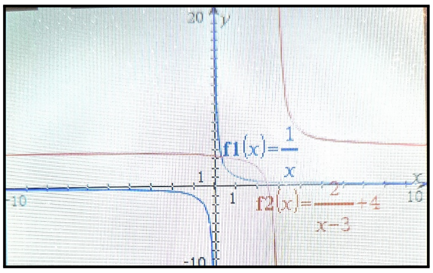
In addition to the ability to create graphs of functions, graphing calculators also have the ability to produce tables, another important tool for problem solving. Solutions approximate to a high degree of accuracy can be found by refining tables with smaller and smaller increments. Thus, with graphing and table features, handheld technology advanced by Waits and Demana plays an important role in casting algebra in different **representations**, one of the essential aspects of algebra noted by Burrill (1995).

Figure 3: Parametric graph of flight of a baseball (Demana & Waits, 1990).



Using function graphing technology to explore the effects of **transformations** on **parent functions** is a prominent theme in Waits' and Demana's texts. For example, the function $f(x) = \frac{2}{x-3} + 4$ is essentially the graph of $f(x) = \frac{1}{x}$ after a horizontal translation by 3 and a vertical translation by 4 and a vertical stretch by 2, with asymptotes $x = 3$ and $y = 4$. If students were to plot this graph by hand without understanding its relationship to the graph of $f(x) = \frac{1}{x}$, we can only imagine how they might connect the dots between the points $(2, 2)$ and $(4, 6)$. Though in fairness to students, I've seen graphing calculators that also connect the dots over the discontinuity at $x = 3$.

Figure 4: Hyperbolic function and parent graph.



Determining asymptotes and end behavior of functions, along with points of intersection, maximum-minima, *etc.*, are ingredients of the **complete graph** of a function, another important feature of the work of Waits and Demana.

The notion of parent functions and transformations is also a feature of later texts including UCSMP's *FST* (Rubinstein & Schultz, 1992, pp. 167) and commercial texts like *Algebra 2* (Schultz & Ellis, et. al., 2001).

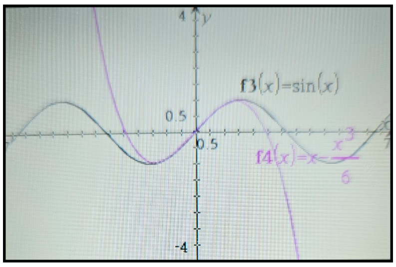
Transformations play a key role in the teaching of mathematics from the early grades through higher mathematics. Children learn early on that figures can be shown to be congruent by a series of slides, flips, and turns. In calculus, students might see that $\int_2^3 \frac{1}{x-2}\,dx$ is essentially the same improper integral as $\int_0^1 \frac{1}{x}\,dx$ after a horizontal translation of 2 units, which is known to diverge. Isometric transformations serve as examples of groups in abstract algebra and geometry courses. (Coxeter's (1961) *Introduction to Geometry* remains a favorite.)

Parent functions are also important when modeling physical situations. Graphing calculators house curve-fitting programs that compute the line of best fit for data that appear linear. One of my favorite examples asked students to use airline tables to determine the distance in miles and length of time in hours from departure to arrival for nonstop flights by similar aircraft found in airline timetables to determine a line of best fit for a scattergram of the data. Graphing calculators readily produced a graph with a clear line of best fit. A slope of about 400 miles per hour and a y-intercept of about 30 minutes gave meaning to those concepts as the speed of the aircraft and the time spent taxiing or awaiting takeoff, yielding a practical guideline for determining flight times ever since.

Technology enables the fitting of optimal models to non-linear data, including quadratic, cubic, square root, exponential, logarithmic, and trigonometric functions. This assumes students can identify the appropriate parent function. For example, I once encountered a text that asked students to fit a parabola to a year's data about heater safety, even though the seasonal data was periodic!

In a fascinating extension to calculus, note how graphing calculator technology illustrates how the third-degree Taylor polynomial $y = x - \frac{x^3}{6}$, which is determined by computing successive derivatives at a *single point* $x = 0$, approximates $y = \sin(x)$ in an *interval* around $x = 0$. For me, the graphing calculator allows me to visualize something that had seemed abstract and uninteresting as something remarkable and beautiful!

Figure 5: Graph of $y = sin x$ with third degree Taylor polynomial approximation.



Function Graphing Technology Extended to Include Teaching Statistics

Greg Foley, currently Morton Chair at Ohio University, provided a broader picture of the capabilities of technology, such as the TI-92, that allow students:

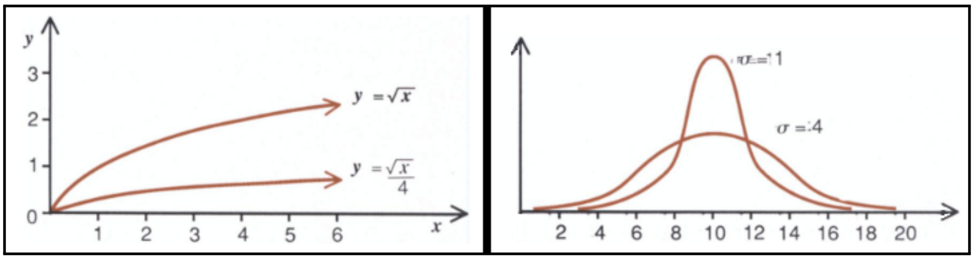
- to operate with integers, rational numbers, real numbers, or complex numbers;
- to define, algebraically manipulate, graph, and tabulate functions of one variable, parametric equations, sequences, polar equations, and functions of two variables;
- to solve equations, find zeros of functions, and factor and expand expressions;
- to define, algebraically manipulate, graph, and tabulate sequences, polar equations, and real-valued functions of two variables;
- to operate on lists, vectors, and matrices whose entries are integers, rational numbers, real numbers, or complex numbers;
- to organize, display, process, and analyze data;
- to write, store, edit, and execute programs; and
- to construct and explore geometric objects dynamically and interactively (Foley, 1998).

Foley also mentioned how technology facilitates teaching statistics and discrete mathematics, citing *Functions, Statistics, and Trigonometry* (*FST*) and *Precalculus and Discrete Mathematics* (*PDM*), the last two courses in the *University of Chicago School Mathematics Program* (*UCSMP*) curriculum.

At the time Waits and Demana were focusing on the use of technology to teach algebra, I was on the advisory board of UCSMP, directed by Zalman Usiskin. I had long agreed with making statistics a component of the high school curriculum. When I was asked to design a fifth-year course for a class of highly talented students at Homestead High School in Wisconsin in the 1960s, I opted to teach one semester of statistics and one semester of calculus, focusing on calculus concepts (like limits) rather than computation.

Like those of us at OSU, Usiskin had long recognized the role of transformations in teaching mathematics. It was decided then that the fifth-year course in the six-year UCSMP curriculum would be *FST*, with Rheta Rubenstein and I as authors of the original edition. We saw that graphing technology could facilitate an understanding of how transformations apply to statistics, as well as to functions. In fact, the similarities between the two are an underlying reason that functions and statistics were combined into the same course in the UCSMP curriculum, as explained in Schultz and Rubenstein (1990). An example is shown in these figures from *The Mathematics Teacher* article.

Figure 6: Transformation from a statistical context (Schultz & Rubenstein (1990).



As an illustration of how the topics are integrated in a course, scale changes of functions and scale changes of data are consecutive sections in *FST*. The example from *FST* in Figure 7 shows of the effect of a scale change on data and its graph.

Figure 7: Effect of a scale change on data and its graph (Rubenstein & Schultz (1992, p. 175)).

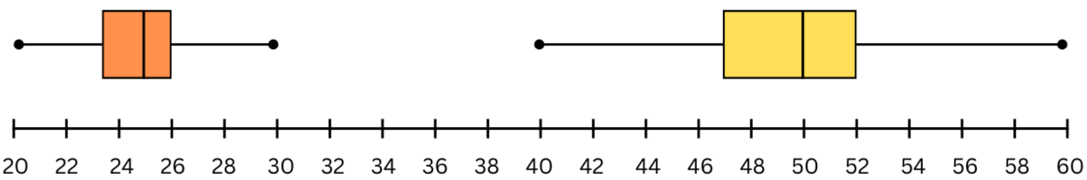
Consider again the data from Lesson 3-3 for the weekly earnings (in dollars) of eleven employees:

40, 46, 47, 48, 50, 50, 52, 52, 52, 53, 60

Suppose that each employee works only half a week.

a. Find the scaled weekly earnings (in dollars).
b. Compare the median, mean, range, and standard deviation of the original and scaled data.

Box plots of the scaled earnings and original earnings illustrate the effects of scalling on both measures of center and spread.



mean:	25	mean:	50
median:	25	median:	50
range:	10	range:	20
variance:	6.25	variance:	25
standard deviation:	2.5	standard deviation:	5

Thus, graphing technology not only brought about a new approach to teaching algebra, but also a new approach to teaching statistics, which became a major component of the widely-used UCSMP curriculum. Giving statistics equal status with functions initiated a major curriculum change for many.

Waits' and Demana's Other Achievements

In addition to what has been written above, these excerpts from their respective obituaries reveal not only their remarkable accomplishments, but also capture the flavor of their personal qualities that contributed to their success.

> Bert Waits was a professor of mathematics emeritus at Ohio State University. He was the cofounder and director of the Ohio Early College Mathematics Placement Testing (EMPT) Program of the Ohio Board of Regents, which became a model for the nation. He authored over 70 publications in internationally recognized professional journals and presented many keynote lectures, workshops, and minicourses at national meetings of the MAA and NCTM. He was a coauthor of the NCTM's 1989 *Curriculum and Evaluation Standards for School Mathematics*. He also served a three-year term on NCTM's Board of Directors and was a member of the College Board's AP Calculus Development Committee. [He also received the NCTM's 2015 Lifetime Achievement Award] ...Known to many as "Hank", he was appreciated not only for his extraordinary contributions, but also for his warmth and keen sense of humor. In his presence others not only learned something significant, but had fun doing it. He was a great friend to many. He enjoyed the last several years with his family in the Florida winter sun (Schultz & Laughbaum, 2014).

> Known for his tireless work ethic, Frank taught Mathematics at THE Ohio State University for more than 30 years, packing in several lifetimes of achievements. ...Described as a "true giant in mathematics education" by the National Council of Teachers of Mathematics (NCTM), Frank never forgot to live by his maxim of helping children. He spent countless hours in inner city classrooms developing new ways to teach high school precalculus and calculus. He wrote or co-wrote dozens of textbooks in use in high schools and universities across the world. He was commissioner of one of the world's largest, locally-run youth sports organizations, Northern Columbus Athletic Organization. Frank's tireless efforts allowed 1,600 boys and girls on the north side of Columbus to participate in softball, baseball, and soccer leagues. A humble man, Frank was always shocked when his work was recognized — including Columbus Jaycees Man of the Year in 1973 and a Lifetime Achievement Award from NCTM in 2015 (The Columbus Dispatch, 2021).

> Waits and Demana were cofounders of *Teachers Teaching with Technology* (*T-Cubed*), the annual *International Conference on Technology in Collegiate Mathematics* (*ICTCM*), and the biannual *International Conference on Technology in Mathematics Teaching* (*ICTMT*). They codirected many mathematics education projects funded by the National Science Foundation. Bert coauthored numerous middle school, high school, and college textbooks, both precalculus and calculus. Together with Frank Demana, Bert Waits received the distinguished Glenn Gilbert Award of the National Council of Supervisors of Mathematics and the Ohio Council of Teachers of Mathematics' Christopherson-Fawcett Award for "inspiration and achievement in education in mathematics" (Schultz & Laughbaum, 2014).

Special Memories of Waits and Demana

Frank Demana was my teacher in an abstract algebra course, when I first came to OSU as a high school teacher on an NSF-supported summer institute working toward my master's degree, years before I met Bert Waits. (The mathematics department notably chose its best teachers to teach in that program.) One day I went to see Frank after class regarding the grading of a test item, the first time I ever talked with him on a one-to-one basis. Frank quickly shifted the conversation to my background. I was struck by how much he knew about me! I learned then how caring Frank was, sensitive to the needs of his students.

Both Frank and Bert had warm personalities that made them liked by all who worked with them, including countless classroom teachers from all over the nation. Nevertheless, Bert didn't like being constricted. This emerged during the NCTM *Standards* writing project, when after weeks of extraordinary hospitality by the Utah Council of Teachers of Mathematics, we found ourselves in a highly regimented atmosphere in a corporate training center outside of Washington, DC. When encountering a dress code of coats and ties for men and heels for women, he promptly revolted, showing up in clashing red plaid shorts and top! No one was going to tell him how to dress!

There was a faction of the OSU mathematics department that not only didn't value the contributions of mathematics education specialists (or statisticians or applied mathematicians, for that matter), but voiced opposition to our efforts. I recall when Waits said he envisioned a day when a mathematician would go to a meeting and say he was from OSU, he would be asked if he knew Bert Waits. I'm confident that he ultimately felt that his wish had been fulfilled, that the department's *mathematics education activity* had earned the respect that it deserved.

Hank Waits and I had a collegial relationship and built an enduring lifetime friendship. This included numerous camping trips with his sons David and Jeff and my son Scott. On our trips to the Smokey Mountains, Hank loved to play the role of a ferocious bear outside the tent where the boys were sleeping. Always pushing the envelope, he didn't hesitate to take his turn on a crude cement water slide in Gatlinburg, the first we had ever seen.

Figure 8: (Left) Bert Waits on a water slide; (Right) Jim Schultz and Bert Waits.

Hank even taught me how to play bridge, now one of my favorite pastimes. After retiring we shared an interest in genealogy. Despite living in different states, we continued getting together with our spouses Barb and Donna. Since then, seeing a TI graphing calculator on the shelves of a Walgreen pharmacy is a poignant reminder of what outstanding colleagues and friends Bert and Frank were to so many of us. The following photos provide a statistically small sample of the wonderful collegial relationships these articles have tried to capture.

Figure 9: (Left) Bert, Jim, and Frank at USACAS (2004); (Middle) Kathy Heid, Bert, and Zal Usiskin at USACAS (2004); (Right) Bert, Joan Leitzel, Frank, Joe Crosswhite (seated) at the home of Peggy Kasten (c. 2012)

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