Why Is This Hard? An Examination of Math Required by Technicians in the Workplace

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Abstract: This article arose from an extensive NSF-funded research project that, through interviews, site visits, and a comprehensive survey, examined the mathematical competencies and conceptual understandings required of entry-level technicians with a two-year college degree. That project confirmed findings from previous studies in that the mathematical operations performed by technicians on the job involved competencies commonly taught in middle school or early high school. Our research went beyond this result, however, by seeking to understand the reasons behind technical students' difficulties with the mathematics they encounter in the workplace and why remedial courses have so often proved ineffective in addressing those difficulties. Particularly in light of changes in the workplace environment being brought about by artificial intelligence and data science, the article has implications for the reform of technical mathematics instruction.

Keywords: mathematics, education, technology, artificial intelligence, math sense, community college

Introduction

As part of a recent NSF/ATE-sponsored project called "Needed Math," the authors have been investigating which mathematical concepts and skills are required for technicians embarking on careers in manufacturing and how these concepts and skills align with the mathematics curriculum and certification requirements that those technicians typically encounter at two-year colleges. Over the past several years, we have gathered data through site visits, interviews with technicians, supervisors, and math and technical educators, and by analyzing survey results of those participants. A detailed description of our findings is available in a separate article [1]. Here, we focus on just one such finding: the fact that the mathematical manipulations required of technicians rarely exceed those taught in middle school, yet the problems they are tasked with solving are often quite challenging. This paradoxical situation, we submit, lies at the heart of the difficulties entry-level technicians often face in the workplace and thus merits the consideration that motivates this article. Moreover, the advent of artificial intelligence (AI) technology may have important implications for the mathematics preparation that will be required for future technicians. We explore those implications briefly at the conclusion of the article.

The finding that all or most of the math required by technicians was covered in middle school is not new [2]. Still, the seemingly straightforward remedy – subjecting students to remedial review courses on that material – has not proved effective [3], [4] and moreover is likely to convince the students and their instructors that they are simply not "math types" and thus unsuited to a career in a technology-rich workplace. The alternative view, and one that we often heard expressed by employers, is that the struggling technician "knows the math but can't use it on the job" [5]. This paper focuses on why that might be so.

Methods

In the course of the Needed Math project, we have developed a series of scenarios: realistic examples of challenging problems technicians face on the job that involve mathematics. These scenarios span a wide range of disciplines from biomanufacturing to electronics, and workplaces from machine shops to bottling plants. Although they differ at a superficial level, each involves understanding *numbers with units*, and it is this commonality that we focus on here.

A Brief History of Number Sense: From Counting to Measurement

Young children learn to count in phases. The first phase involves memorizing a sequence of words – "one," "two," "three" – in a certain order. This typically coincides with memorizing a different sequence of sounds called "letters": the alphabet. The two sequences are quite different, however. For one thing, the alphabet is finite, whereas numbers literally "go on forever." And while letters are used to form words, numbers are used to *count things*.

Counting is not a trivial process. At a very early age, long before they enter school, most children are taught to count the objects in a set by pointing to each in turn, "naming" them according to that memorized number sequence, and then, for some reason, only paying attention to the last number. Contrast that to the equally plausible process of naming objects by letters – where every name "sticks" to the object named and thus the order of naming is important – and you see how the purpose of counting is not immediately obvious.

Counting answers the question "how many?" and the last number enunciated is the answer – in mathematical terms, the cardinality of the set of objects counted. That fact leads to the first-learned arithmetic operation – addition – which answers the related question, "how many after I add these?" which leads to "how many after I take away these?" and we're off to the mathematical races.

And then we introduce the idea of *measurement*, and instead of asking "how many?" we ask, "how big?" or "how heavy?" or "how long until?" and life gets more complicated because now our numbers have units associated with them.

Once we start measuring things, we discover that the numbers that have served us so well – the positive integers, or so-called natural numbers – don't suffice to answer the new questions. A table may be longer than 6 feet but not quite 7 feet long. We can revert to a smaller unit, but the table may turn out to be longer than 80 inches, but not quite 81. So, unless we want to use smaller and smaller units, we are forced to introduce numbers that lie in between the integers and to teach various ways – fractions and decimals, for instance – to represent such numbers.

This leads to another concept: precision. As long as we used only numbers for counting things, we didn't have to worry about getting the right answer. It might be tedious, but in the long run, we could always figure out the correct answer to the "how many?" question. But measurements are never entirely accurate. No matter how hard you try, you can never know to arbitrary precision what the answer to a "how long?" question really is. So the best you can do is to come up with two numbers: the answer you got when you made the measurement and the precision, or "expected error" of that measurement. How you figure out that expected error no longer resides in the domain of numbers and their representations: it involves several new concepts: distributions, populations, samples, and the various statistics, like mean and variance, that are used to describe them.

Variance and the related concept *of tolerance* are of particular importance in manufacturing, where products and components must meet specific specifications. The desired length of a machined part, for instance, may be specified as a number followed by a tolerance, measured either in absolute units or as a percentage of the desired length. The arithmetic operations involved in translating tolerances, so specified, to maximum and minimum allowed values are admittedly the stuff of middle school math. However, understanding what those tolerances mean in practice and how they might affect workflow requires a robust understanding of sampling error, both in the manufacturing process and in the measurement itself.

Not all quantities lend themselves to direct measurement – some involve calculation. The area of a rectangular planar surface is the product of its height and its width, and the units of that area differ from those of the length dimensions used to measure it. Likewise, the density of a solid is a measure of its mass divided by its volume, and the units of density reflect that relationship: grams/cm^3 or tons/acre-inch, for instance. For newcomers to numbers used as measurements, the idea of deriving new units by multiplying or dividing old ones is mysterious in itself and raises the question: if it's OK to multiply and divide different units, why can't I add and subtract them?

It is a common observation among instructors [6], [7] that derived measurements and their units are more difficult for novices to grasp than the primitive quantities that compose them. For example, biomanufacturing students often have trouble distinguishing concentration from quantity in solutions, and students of mechanics may confuse density and weight. The difficulty is exacerbated when the primitive units themselves are somewhat mysterious: the relationships between voltage, current, resistance, and power is a case in point and results in many students resorting to various visual aids such as Ohm's Law triangles [8] that serve to remind them, for example, that "current equals voltage divided by resistance" without attempting to clarify what that sentence actually means or how it may apply to a real-world problem.

From Numbers to Variables

Ohm's law describes another feature of measurements that can lead to confusion: a change in one thing can result in a change in another – measurements, in other words, can be related to one another, meaning that one measurement may depend on another. The pressure at the bottom of a water-filled cylinder depends on the height (but, mysteriously, not the width) of the column of water; the pressure inside a balloon depends on the temperature of the gas inside it. And the relationship can be more complicated than these: the distance a projectile will travel depends, in different ways, on the speed and angle at which it is launched.

By introducing such dependencies among measurements, we have subtly moved away from the measurements themselves, thought of as numbers. The statement that measurement A is related to measurement B is not a statement about numbers; it describes how those numbers are *related*. It implies that if you change A, B will change in a predictable way. Similarly, the statement A = 2B + 4 implies nothing about the value of either A or B; it is a description of a relation between those quantities, expressed as an algebraic equation. Neither A nor B is a number; they are *variables*.

One may think of algebra as follows: one is presented with a sequence of numbers, arithmetic operations, possibly some parentheses, an "equals" sign, and a single letter, often "X," the latter possibly making more than one appearance on either side of the equals sign. Such an object is denoted as an "equation," and the assigned task is to perform a sequence of manipulations on this equation that will result in isolating the X on the left side of the equals sign with a single number on the right, an operation described as "finding X." In this context, X is not a variable; it is an unknown. Consequently, the important concept of dependency never arises. The difference between these contrasting interpretations of algebraic relationships is critical to the tasks that technicians are confronted with, but does not make its appearance in the standard curriculum until Algebra 2.

A Real-World Example

In the training of technicians planning to enter the field of biomanufacturing, a key process is the preparation of solutions: mixtures of an inert liquid, often water, denoted the "solvent," and one or more substances, called "solutes." Often, the solutes are packaged in the form of solutions themselves, usually in a form too concentrated to be useful in practice. Thus, they must be diluted to reduce their concentrations to a prescribed value.

Concentration, the amount of solute per unit volume of solution, is thus a central concept underlying the process of dilution. It is a compound measurement, and its units (e.g., milligrams per liter) reflect that fact. Moreover, it is an *intensive* quantity, meaning that, assuming that the solution is well-mixed, every portion of it has the same concentration of solute. The process of dilution, then, consists of pouring a certain volume of solute with a given concentration into a certain volume of solvent in order to produce the desired volume of solution with the desired concentration.

If that sounds confusing, it's because it is! It ought to be simple, but there are just too many confusingly similar variables involved: even with only one solute, there are three different volumes and two concentrations.

The situation is simplified, at least superficially, by a deceptively simple formula:

$$C_1 V_1 = C_2 V_2$$

Where C_1 is the concentration of the solute before dilution, V_1 is the volume of the solute required, C_2 is the desired concentration of the solute after dilution, and V_2 is the volume of solution desired.

And that, some would say, is that. But is it really? Have we really simplified things by condensing everything into an equation?

Consider that the equation involves two volumes, V_1 and V_2, but the statement of the problem involved three: the volume of the solute, the volume of the solvent, and the total volume of the solution (which is the sum of the other two). So which volume is V_1 and which is V_2? According to the description above, V_1 is the volume of the solute, and V_2 is the volume of the final solution. But recall that the process of making up the solution involves mixing a different pair of volumes – the volume of the solute and the volume of the solvent – and it is easy to mistake those for the volumes represented in that equation. Clearly, the equation itself, though easily remembered and deceptively straightforward, is also easily misinterpreted. And the situation just gets worse when there are multiple solutes involved or when the dilution itself requires multiple steps.

There are two distinct ways to understand an equation like the one above. One is to treat it as an exercise in "finding X" – here, the unknown V_1, given numbers for the other three factors. This involves manipulating the equation to isolate the unknown and then plugging in the numbers for the three "knowns" and doing the requisite calculation. The alternative approach is to recognize the equation as a statement: *the amount of solute doesn't change during the dilution process*.

When you extract a volume V_1 from a solute solution with concentration C_1, you are extracting an amount $C_1 V_1$ of solute. When you dilute that amount of solute by adding solvent, resulting in a new volume V2, you are not adding or subtracting solute. The amount of solute stays the same, but its concentration changes to C2. The amount of solute didn't change; in other words, $C_1 V_1 = C_2 V_2$. That's what the equation means, and that's why the equation is true.

Some Changes Happen Gradually

The dilution example above is an instance of a discontinuous change; the concentration changes abruptly when you make the dilution. But technicians regularly encounter situations where measured quantities vary continuously over time. Drill bits penetrate metals at specific rates; etching of semiconductor wafers is a time-dependent process; and the temperature of the material in a heat exchanger varies along its length as the material moves through it. All of these rates of change are variables, dependent on external factors; many of them are not constant, but are themselves subject to change over time.

The field of mathematics that describes such continuous changes – calculus – is generally considered too "advanced" to be included in the technical math curriculum – and admittedly, few technicians will ever be required to apply the chain rule for differentiation or to integrate by parts. But the complementary concepts of rates and accumulations, though not explicitly named "derivatives" and "integrals," are nevertheless fundamental to understanding and working with processes that involve change over time. Once again, the important math competency lies not only in knowing how to calculate something, but in understanding what is being calculated.

The distinction is all the more important in the context of recent technological advances.

Results and Discussion

With the arrival of ChatGPT and its many competitors, we face a situation analogous to the introduction of cheap calculators to the math classroom. The arrival of the calculator did not relieve students of having to learn mathematics, but it did affect which mathematics they needed to learn. Armed with a calculator, students no longer needed to know how to use pencil and paper to divide two numbers, but they did need to understand and interpret the calculator's answer. They needed to understand, for instance, why dividing 1 by 2, 4, or 5 gives a short answer, while dividing by 3, 6, or 7 gives a long one; to understand that 0.24879 is smaller than 0.25 even though its decimal representation is quite obviously bigger; to understand why swapping the order of operations sometimes changes the answer and sometimes doesn't. The ability to estimate a result became important: knowing that 1.94 times 3.52 should be close to 7 helps one realize that something is wrong when the calculator returns 682.88 as an answer.

In the Age of Artificial Intelligence, How Much Math is Really Needed?

The workplace tasks we have identified call for two levels of mathematics: syntax and semantics. The syntactic level includes the skills that are needed to perform certain operations and the procedures those skills enable; the semantic level requires understanding the concepts that lend meaning to those operations. We have argued that although the calculations required to perform common tasks are relatively straightforward, the concepts underlying them are often abstract and easily misunderstood, making the tasks themselves more difficult than they appear. But the advent of artificial intelligence (AI) raises an intriguing question: in an AI-enabled work environment, what mathematics will technicians need to do their jobs? After all, if ChatGPT can knock off a passable sonnet in iambic pentameter or create a working computer program in seconds, why won't future technicians simply follow step-by-step instructions handed down by an app on their phone? In that event, what math will they need?

At this early stage in the development of AI, nobody really knows, but results from the Needed Math project can provide a pointer. Toward the end of the project, building on ChatGPT, we developed a scenario generator, a tool for producing realistic, math-rich tasks relevant to particular industries. The user, typically a math or technology instructor, develops a prompt along the lines of "Make a scenario involving deposition of a conducting layer in the fabrication of a microchip." and the tool generates a scenario involving a description of the task together with an explanation of the mathematics that it entails, as well as pedagogical suggestions and other resources for the teacher.

When we have presented the scenario generator to instructors, their reaction has been uniformly positive. Math instructors see it as a gateway to a wide range of technology-rich occupations that they cannot possibly have detailed knowledge of, enabling them to contextualize the math they teach in real-world contexts. Technical instructors view it as a valuable guide for making explicit the mathematical concepts embedded in the skills they teach. Both groups see the tool as a way of enhancing their productivity and making their teaching more relevant and engaging to their students.

Thus, the scenario generator has the potential to bring the two groups of instructors together, to the benefit of both. To the extent that an increasingly complex technological world calls out for compelling answers to the question, often raised in math classes, “When am I ever going to use this?”, artificial intelligence, like other technologies before it, may offer solutions for some of the problems it will undoubtedly produce.

But the success of the scenario generator raises an important question: if the teacher can use it to produce scenarios representative of the types of challenges their students are likely to face, what is to prevent those students from using the same technology to help them meet those challenges? And in that event, what was the purpose of teaching them the math in the first place? True, AI agents like ChatGPT are, at least at this writing, still prone to “hallucinations” in which they produce incorrect and at times bizarre results. But it would be foolhardy to assume that this problem will prove insoluble over the long term or, for that matter, to suppose that manufacturing firms will fail to integrate AI into their workplaces in the very near future. What does that imply for the math that future technicians will need?

One can imagine a future in which technicians are able to carry out instructions offered by an artificial intelligence agent without understanding their purpose, but are incapable of adapting to new situations, of troubleshooting error conditions – in short, of thinking on the job. But such an outcome would likely lead to costly disasters, and employers will be reluctant to hire technicians who see the factory as a black box. As AI assumes responsibility for automating the syntax of a task, the technician will increasingly be tasked with providing the semantics, anticipating and troubleshooting problems, and guiding the smooth operation of a complex multi-step process. With much of the calculation automated, the mathematics required to act in this supervisory capacity might better be characterized as abstract reasoning, here defined as the ability to deal with concepts and entities that cannot be directly perceived or manipulated. Mathematics provides the necessary tools – models, representations, algorithms –to support such reasoning.

Conclusion

The ability to multiply two three-digit numbers or compute a percent is, by itself, useless whether it is accomplished with a pencil or a calculator. The value of such operations derives from their use in achieving something else of value. That’s why mathematics education did not vanish when calculators appeared. An AI agent can break down a complex process in the form of a sequence of instructions to a technician; it can even explain the rationale behind those instructions. But a technician who doesn’t understand what is going on “under the hood” will be at risk of making potentially catastrophic mistakes, and increasingly, such understanding requires the abstract reasoning that mathematics enables. The workplace changes that AI seems poised to make strongly encourage us to teach mathematics to future technicians as a means for understanding and adapting to an increasingly complex world.

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