Thomas A. Easton

# Beyond the Algorithmization of the Sciences

## Algorithmic thinking is transforming both the descriptive sciences and the humanities, bringing them all closer to the mathematical core of computer science.

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Computer science has transformed biology and other scientific fields and now promises to transform even the humanities. One result is a reciprocal demand for new ways of teaching such computer science basics as algorithms and computation.

One might view the transformative effect of computer science in terms of the increasing reliance on computation, replacement of paper library collections with online databases, use of online resources by students writing papers, and even the way search engines are changing our sense of how we know what we know; many of us feel that knowledge isn't real unless it can be Googled. But these transformations may not threaten to displace mathematics as the queen of the sciences but are forcing educators to consider both the place of algorithmic thinking in the curriculum and practical approaches they might use to inculcate it.

When I went to graduate school many years ago, the sciences were ranked—at least unofficially—in a hierarchy. The queen of them all was mathematics [3] for at least two reasons: it was so useful it was known as the "handmaiden of the sciences" [2], and it was "pure" due to its focus on abstraction and formal logic. Pure math was the highest form of math, and its practitioners had long prided themselves on having little or nothing to do with the real world.

Nearest the queen's throne were the higher courtiers, the more mathematical, or "hard," sciences—astronomy and physics foremost, followed by chemistry. Computer science, initially a field for math majors only, suffered from its lack of purity, though, like physics, astronomy, and chemistry, it was very useful (see the accompanying figure). The "soft" sciences included biology, geology, psychology, and sociology. They were not only less mathematical but seemed at times to actively resist mathematical treatment. They were more descriptive than analytical, relegated to the fringes of the throne room, and viewed as having less value than their hard counterparts.

It is not unreasonable to say they suffered a bit of an inferiority complex. Indeed, the seriousness of these feelings is attested to by the effort that had already gone into mathematizing biology. Prominent names in that effort were researchers D'Arcy Thompson, Alfred Lotka, Vito Volterra, and Nicholas Rashevsky. Rashevsky founded the Committee on Mathematical Biology at the University of Chicago [5], where I arrived in 1966.

The aim of mathematical biology was (and is, under its current name "theoretical biology") to discover the equations that describe biological phenomena [6]. It has enjoyed considerable success, particularly in biophysics and population biology, but not so much that biology as a whole has come to be regarded as a particularly mathematical science and therefore closer to the queen's throne.

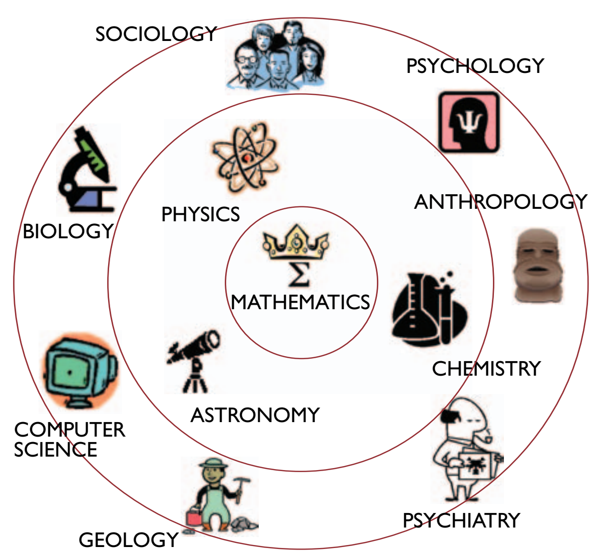
Meanwhile, biology has earned renown for its advances in genetics, evolution, immunology, and embryology. These fields all reflect a growing understanding of process, or the sequences of steps involved in making biological things happen. Biology is no longer merely a descriptive science; process gives it genuine predictive power. Process also makes biology kin to computer science. To a computer scientist, a process is an algorithm, defined as an ordered sequence of instructions for accomplishing a task. The instructions must be executable and terminate. In biology, important algorithms include evolution by means of natural selection, the replication of DNA, and the generation of antibodies against disease organisms. They are even found in the behavior of social insects [1]. The math seen in biology is more concerned with rates and equilibria than with what takes place within a cell, an organism, or a population. In biology, there are no equivalents of physics' equations of motion.

If we view evolution as an example of a biological algorithm, the task in question is how to produce a creature adapted to a specified environment. To be even more specific, let us attempt to produce bacteria that thrive despite being doused with some amount of antibiotics, following the instructions spelled out in the box in the next page. Note that this algorithm produces a result—adaptation—without specifying the details or mechanism of the adaptation. The bacteria may have acquired the ability to excrete the antibiotic or to digest it. They may have modified their internal chemistry so the antibiotic no longer affects them. Our understanding of the process of natural selection has definite predictive power, but that power does not extend to all details. We can say the same thing about physics, which has a precise mathematics of ensemble behavior, also known as statistical mechanics, that does not describe the behavior of individual particles.

Algorithms have thus made biology as useful a science as physics, chemistry, and computer science. But are algorithms enough to move biology closer to the throne? Are they math?

Five decades ago, most mathematicians would have said no. Then in the 1970s, they discovered the value of computers for "proving" theorems (such as the four-color map theorem) by working through exhaustive lists of cases. Such proofs were initially controversial, as many mathematicians objected to the lack of formal methodology. However, mathematicians eventually accepted them as the equivalent of traditional proofs [4]. The algorithm, or process, had found a home in the purest of mathematics.

Also worth noting is that physics, astronomy, and




The hierarchy of the sciences.

chemistry have all come to rely on computer simulations—based on yet more algorithms—to understand events and processes that do not yield to mathematics. Many hard scientists today think at least as much in terms of algorithms as they used to think in terms of equations. At the same time, biologists are collecting vast amounts of data (such as in the various genome projects) that to some of them promise to reduce life to chemistry. However, life cannot be understood except in terms of processes and may be calculable only through computer simulation and visualization. In this way biology is more and more like the traditional hard sciences of physics, astronomy, and chemistry. Increased predictiveness may elevate biology's status in the hierarchy capped by the queen, though so does the increased respect for process, or algorithms.

A similar transition is happening in several other descriptive sciences. Process plays a central role in geology, psychology, and anthropology, though it perhaps plays less of a role in sociology and other social sciences. We may also claim that computer science and algorithmic thinking are dragging at least some of the erstwhile soft sciences closer to the throne of the queen, mathematics. Many of those who still call mathematics the queen of the sciences now recognize biology and geology as hard sciences on the same rigorous scientific level as physics, astronomy, and chemistry, rather than as soft sciences. This is due to the growing recognition of the value and power of algorithms, or process, and is in turn due to the pervasiveness of computer science, including in mathematics. It is only a matter of time before other soft sciences are drawn closer to the center of the royal court as well.

Mathematics and algorithms are so essential to computational thinking that computer science will retain its historical emphases on these topics. Other fields that, like biology, have sought to mathematize their content will find that, because mathematics has incorporated algorithmic thinking, they might get closer to the queen by emphasizing algorithms over equations. Resistance is likely to be strong in the humanities, but even there algorithmic thinking is becoming essential. For example, it has found a niche through the way computers are used to verify that classic texts and artwork are properly attributed to their creators, to detect plagiarism, and even to aid the creative process.

More and more educators will have to grapple with the need for courses that inculcate algorithmic, or process-oriented, thinking. This might mean students will take more computer science courses. If this happens, computer science educators may need to redesign those courses to emphasize algorithmic thinking in ways that satisfy the needs of students in other fields, including those with only a distant relationship with mathematics.

**Natural selection can be understood as an algorithm expressed in near-pseudocode form in the following six instructions:**

1. Begin by choosing a creature (here a bacterium) that thrives in a suitable environment (here a Petri dish of nutrient jell);
2. Choose a target amount of antibiotic for the bacterium to tolerate;
3. Alter the environment in the direction of the target, adding a little antibiotic to the jell;
4. Let the bacteria multiply; the offspring that have trouble dealing with the change in the environment (the antibiotic) will multiply less successfully;
5. Repeat instructions 3 and 4; add more antibiotic and let multiply;
6. When the amount of antibiotic matches the target amount, repeat only instruction 3; a growing bacterial population demonstrates that the algorithm has succeeded.

**The natural selection algorithm.**

This will require adding to the classics of computer science (such as the binary search and knapsack algorithms) the additional algorithms of natural selection, antibody generation, DNA replication, plate tectonics, and more. One result will be a better understanding of the processes at work in various fields of knowledge. Another may be that researchers will be inspired to express their knowledge in algorithmic form, with potentially significant results. **C**

## References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