Values, Methods, and Facts: How Do Math and Science Align and Differ from the Perspectives of Mathematicians and Biologists?

Rachel Rupnow
Northern Illinois University

Margaret Remus
Northern Illinois University

Nicole Scheuermann
Northern Illinois University

Heather Bergan-Roller
Northern Illinois University

Despite the interrelated nature of math and science, limited work has characterized mathematicians' and scientists' beliefs about each other's disciplines or courses. In this study, we use nine interviews with mathematicians and biologists to characterize the interrelationship of community values, methods, and accepted facts in math and science and their relationship to introductory courses. Results include similar descriptions of biology and of what scientists do by all participants, but differing characterizations of what math is and what mathematicians do and claims that math courses do not teach students what they need. Implications include a need for the mathematical community to better align introductory course material with their values so that people outside the community better understand what mathematicians value and do.

Keywords: Interdisciplinary Education Research, Nature of Math/Science, Disciplinary Norms

Cross-disciplinary research connecting math and science education is a relatively new but burgeoning area of work. Much of this work has emphasized content connections, including how specific math-based content is learned and used in biology (e.g., Robeva et al., 2010; Williams et al., 2021), chemistry (e.g., Bergman & French, 2019; Jones, 2019), and physics (e.g., Jones, 2015; Schermerhorn et al., 2022; Serbin et al., 2020; Serbin & Wawro, 2022). Nevertheless, much work remains to be done at the interface of math and science education, especially as it relates to beliefs about teaching and the nature of math and science. In particular, we address the following research questions: (1) How do mathematicians and biologists characterize the nature of math, science, and biology? (2) What, if any, connection is there between how mathematicians and biologists view and want students to take away from their own and each other's disciplines?

Literature Review and Theoretical Perspective

Extensive work has characterized beliefs in math and science separately. Math educators have studied teachers' beliefs about math, teaching, and learning in K-12 and university contexts (e.g., Melhuish et al., 2022; Philipp, 2007). Much of the university-level work has focused on beliefs underpinning pedagogical approaches, such as influences on pedagogy (e.g., Johnson et al., 2018) and pedagogy in active-learning and lecture-based classrooms (e.g., Fukawa-Connelly, 2012; Woods & Weber, 2020). Moreover, work has examined perceptions of the nature of math (e.g., Ernest, 1989; Rupnow, 2021), including views of math as a disconnected set of tools, something discovered, or something created by mathematicians. Characterizations of science beliefs have focused on teaching influences (e.g., Al-Amoush et al., 2014; Rupnow et al., 2020); certainty of knowledge in science (Urhahne et al., 2011; whether views of science disciplines differ (Topcu, 2013); and descriptions of the nature of science (Southerland et al., 2003).

Studies attending to university math and science education simultaneously have been more limited. Apkarian and colleagues (2021) characterized instructional practices in math, chemistry, and physics, with special attention to active learning uptake. Reinholz and colleagues (2019) examined disciplinary cultures in biology, math, chemistry, and physics based on data from discipline-based education researchers at a cross-disciplinary education conference. From their work, they concluded that while STEM is often treated as one entity, meaningful differences exist between disciplinary cultures. Moreover, to our knowledge, research has not examined mathematicians' and scientists' beliefs about each other's courses and views of their disciplines, despite the impact understanding each other's perspectives might have on determining programs of study, who is best positioned to teach courses, and appropriate content in service courses.

Based on this background, we adopted Laudan's (1984) Triadic Network of Justification to frame our examination of faculty beliefs and their relation to introductory courses. The Triadic Network of Justification is grounded in philosophy of science and examines the interrelationship of axiology, methodology, and factual claims within a field's decision-making. In particular, a field's axiology (espoused values and principles) influences what counts as an acceptable methodology just as the feasibility of methods constrain what can be valued by the community. Similarly, use of acceptable methods impacts whether an assertion can be stated as fact while accepted facts within a community impact the methods that will be employed for exploring new areas. Finally, what is accepted as fact impacts the values of the community just as the values of the community impact what is acceptable as a fact. Laudan's work has been employed in math education research to examine the values (axiology) upheld through proof norms (methodology) (Dawkins & Weber, 2017). Here we will examine the values, methods, and accepted facts as taught in introductory courses in math and science and contrast their alignment in the two fields.

Methods

This research effort represents an interdisciplinary collaboration of math, statistics, and biology education researchers, and we believe our respective positionalities inform and enrich the research. Two members of the team are Assistant professors and two are graduate students. One member has extensive experience doing qualitative coding of interviews, and the other three have an intermediate level of experience. Our varied statuses and prior experiences impacted how we interpreted the data, and we worked to value and incorporate everyone's insights.

We audio-recorded interviews with five mathematicians and four biologists (nine total) at two R2 universities in the same state. One researcher, with a math education background, interviewed all participants for 60-90 minutes over Zoom or in-person. Interview questions focused on the nature of math, science, and biology; how these disciplines are learned; and how introductory courses in these disciplines are taught. Gender-neutral pseudonyms were assigned such that math faculty were given names starting with M and biology faculty with B.

The interviews were iteratively analyzed in accordance with thematic analysis (Braun & Clarke, 2006). First, two transcripts were open-coded by two authors who attended to prior work characterizing math and science but did not enter analysis with particular codes in mind. Those authors condensed and organized the open-codes into focused codes and applied them to the same transcripts. After refining, all authors independently coded the remaining transcripts, with at least two authors coding, discussing, and reaching consensus on each. This led to minor coding additions and refinements, and revisions were applied to earlier transcripts. Finally, all authors discussed clarity and themes, which led to adoption of the theoretical perspective. Final codes were aligned with the theoretical perspective and applied throughout the transcripts.

Results

Axiology: Cultural Values in Math and Science

Math knowledge, once gained, is definite and science is continually evolving. Participants noted many distinctions and similarities between math and science as fields. One distinction agreed on by mathematicians and biologists was that math knowledge, once gained, is definite and science is continually evolving. For example, Max said, regarding math and biology:

> It's my impression that biology as a discipline evolves at a so much faster pace than mathematics does. Mathematics absolutely expects that the calculus that you learn in calculus...is valid, will be valid, is state of the art....In biology...what was thought to be state of the art when you came in as a freshman might not be...by the time you leave.

Further, the idea that math is more certain than science, which thrives on constant evolution, was presented by many participants. Blake claimed, "If you put 10 mathematicians looking at the same data, all 10 should come up with the same answer, whereas in physics, chemistry, and biology I suspect that you'd get a lot more variation." Not only does this biologist see math results as more definite than results in science, but math results are also more widely accepted.

Math and Science are siloed/are separated by jargon. Several participants suggested silos or disconnections between disciplines might exist due to the need to specialize within one's own discipline. Brooks noted divisions even within disciplines: "even within biology, the medical biologists and the environmental biologists are completely different, and they don't communicate with each other." Further, several participants suggested differing cultures can create divisions between disciplines. Max noted the impact of being part of a culture on how one sees the world:

> It instills in one a discipline, whether it's history or math, or physics, or accounting, or whatever. Everybody who has been through a discipline has acquired a certain lens with which they see the world, and that lens is not unique to that individual...you share with others this way of thinking and seeing things that you, you can recognize as part of a community of thought...Each individual may bring their own little nuance to it. But...we recognize mathematics as a community of thought, and people in...a shared language.

Knowing the in-group approaches and language are part of becoming a member of a discipline, whereas not knowing them could make it difficult to communicate across disciplines.

Math is what mathematicians do/anyone can do science. Participants suggested that math is characterized by mathematicians' actions, but anyone can do science. Max, Morgan, and Marley claimed "math is what mathematicians do" when initially defining math. In contrast to math's community-membership focus, many participants reversed this in science, where anyone who acts like a scientist is part of the scientific community. Brooks stated:

> I think science is any investigation of something unknown. It could be anything we typically think of as physical sciences...but I also think it can just be trying to figure out something that you don't know in any sense. I know Adam Savage from Mythbusters says that everybody is a scientist, and I kind of agree with that mentality.

Similarly, Bailey noted "the scientist for me is someone that at least follow[s] scientific reasoning." These comments suggest that someone who engages in scientific processes is a scientist, whereas who does the activity determines whether something is math.

Science is a cross-disciplinary search for knowledge. Both math and biology participants emphasized the value and necessity of cross-disciplinary knowledge and interaction. Biologists discussed how different disciplines within science can work together to make each stronger, such as Blake's comment on students seeing methods in one area of science applied elsewhere:

> I think because of teaching and reiterating that scientific method and showing, for example, a physics student that the same scientific method you use over in physics can be applied in biology is really important for some of that connectivity....Anytime a biology student can broaden their knowledge base in other STEM fields, the more well equipped they are to ask less biased questions within biology.

Math is a tool. Relatedly, there was consensus that math acts as a necessary tool within science. All biology participants said math was an important tool within their discipline, many specifically using the word "tool". For instance, Blair said, "[Math is] providing some tools of how you describe biological processes quantitatively, in terms of models." Others, such as Blake, went further and did not see any applications for math beyond use in other fields:

> That sounds harsh, but I think that is how I think of [math]. So, it doesn't really have applicability on its own other than it's a tool. But it's like *the* tool all, all right to be used in all of these other fields....[italics are participant's emphasis]

Note this biologist sees applications of math in concert with other areas, just not on its own. Mathematicians, such as Mo, also referred to math's utility in problem-solving: "You use the mathematics to understand different parts of the world, different sciences, and also a lot of things that are not typically considered science, but you use it to analyze things."

Biology is the study of life. All participants characterized biology as the study of life. Max expanded that definition to include "the processes that make up life". Marley further included what biologists do, incorporating topics adjacent to life: "I mean, a biologist is not going to study something that's inanimate. It's going to be studying life or things that are very close to life, like viruses. They're not really alive, but they have an impact on life." Biologists described biology as the study of living things or organisms. Three of the four biologists provided an expanded definition of biology that incorporated biological systems, such as Bailey:

> So biology is a study of living things. And it can be as an organismal... for example, where the organism lives, their habitat. Then you zoom in animals by themselves, the behavior, then up to how a cell work[s]. And there's connection between all these.

While biologists were more precise and provided more nuance in their responses, mathematicians and biologists largely agreed on what biology is about.

Math is about patterns or numbers. Biologists largely described math as the study of numbers, such as Blake: "So thinking about how numbers may…relate to one another in new ways...coming up with new sorts of theories or laws or rules as to how numerical relationships correspond to one another or relate to one another." In contrast, mathematicians mostly focused on patterns and relationships with some references to numbers, such as Miller:

> If we have to add restaurant bill or divide restaurant bill, [my friends] say, "Oh, you're the mathematician, you do it," the joke is. And I say, "Guys, that's not mathematics. That's arithmetic." So, the definition of mathematics is not addition, subtraction. The definition of mathematics is to study how mathematical objects relate to each other, the rate of change, the tools and methods that are required.

While math includes numbers, Miller suggests math is about relationships among objects.

Methodology: Ways of Doing and Learning Math and Science

Science is done by the scientific method. All mathematicians and biologists described science as being done and/or connected by a systematic approach, especially the scientific method. For instance, Blake referred to the scientific method numerous times, including: "I guess [science] is a way of studying, a way of understanding…. when I think of science, I think of the scientific method." Mathematicians also focused on the systematic approach to data collection and analysis when defining science, such as Marley:

> Sort of the study of nature, but it's a little bit more than that. So if you allow me to give a definition that's as broad as my definition of mathematics, I think it's just...It's observation and analysis....There has to be observation. There has to be analysis to search for patterns.

While particulars varied, references to the scientific method or aspects of it, including hypotheses, data collection, analysis, and repetition consistently appeared across participants.

Math is done via proof or unknown. Mathematicians often characterized doing mathematics in terms of proof and logical deduction. For instance, Morgan observed:

> What do mathematicians look at? Well, they look at things that interest them. And it's usually not just, "Hey, where can I get—starting with these assumptions, where can I get just using rules of inference?" It's not so interesting work. You can take Peano arithmetic and say, "Okay. Well, what follows from that?" Well, no, look at things that interest us.

While mathematicians are expected to demonstrate results through a sequence of logical deductions, interests are also expected to play a role in mathematicians' approaches to research. In contrast, biologists expressed uncertainty about what mathematicians do. For instance, Bailey tentatively suggested mathematicians use the scientific method to focus on calculations:

> Maybe, I'm wrong, but I think you have a question. You want to demonstrate something. You have a hypothesis, so you will write down on top of your page what you—or, I don't know how you do it. And then you start to make equation and see if you can solve it.

Blake professed even broader uncertainty:

> Any time I've talked to someone who does theoretical mathematics it is, it is at its intro level of being explained to me so far over my head and so jargon filled that I can't pull from it the applicable aspects to my field. So I can't really explain to you what theoretical mathematics is other than it's, you know, developing theory in math.

Of note, while everyone seemed reasonably confident in characterizing what scientists do, biologists expressed uncertainty and/or differing characterizations of math than mathematicians.

How Learning is Approached. In addition to characterizations of how researchers do math and science, we also note approaches to learning math and science, as they could be considered ways to show appropriate methods for engagement in those fields. The most common description of how people learn math was through exposure and repetition. For example, Mo said, "A little bit like you acquire speaking skills. You see it used and mimic it and learn some things on your own." In contrast, the participants described how biology is learned through hands-on activity, including experiencing the natural world and research experiences. Brooks claimed:

> I think a lot of people learn biology growing up through experience...learning what animals are…these sorts of things people often learn before they've ever taken a biology course. And getting out into nature is often a way that many people get into environmental fields because they always loved going out to nature, going on hikes, watching birds...And then all of the human health pathways are a little bit more obvious because if you experience your own healthcare, you see how that works.

Further, the participants described how learning biology is done through research experiences. For example, Max noted students can do research even as undergraduates: "Biology, I think it's really possible for a undergraduate, you know, Junior, to be doing a real research project."

Factual Claims: Key Facts within Math and Science Taught in Introductory Courses

While accepted facts in math would include proven theorems or formulas and in biology might include widely accepted theories like cell theory (all organisms are made of cells), here we emphasize instead content students are likely to take away from their introductory courses.

Content in biology introductory courses. All the biologists made a distinction between what biology is taught at the introductory level for students majoring in biology (i.e., "majors") and those not (i.e., "non-majors" such as humanities majors, business majors). For example, Blake described how both versions of the introductory courses cover similar topics but emphasized forming a solid foundation of concepts and skills for majors to build on:

> I think the goal for non-majors is to provide them with background content on what biology is, so that it is the study of living organisms to provide some background content on the breadth of organisms that exist…and then do some introductory lessons on the scientific method, and some of those patterns and processes that we get into in later biology..... For our majors...teaching the same stuff that we're doing with non-majors but doing it at, with the expectation that they are going to build on that knowledge. So really driving home the scientific process, which they're going to use throughout the rest of their, their major, really driving home some of the core concepts in biology.

Of note, biologists claimed biology majors' first courses in college are meant to provide opportunities to engage with biology in the same manner as they would in subsequent courses, and non-majors' courses provide a similar experience, just with less detail.

Content in math introductory courses. In contrast, multiple math and biology participants noted math introductory courses tend to teach separated procedures and content that mismatches what is needed. For example, Brooks described the non-applicability of differential equations:

> Differential Equations, the only thing I took out of that class was learning how to do the math if I was filling up a bathtub that was emptying at the same time, right? That was all I saw in Differential Equations, so I think I do inherently just think of things in that sense and where is this coming from? Where's it useful for?

They later noted they appreciate math is "something behind the scenes… it's just a part of the whole system" but math is not taught in such an integrated way, instead "taught as a separate thing". The mathematicians agreed math is taught in a way that does not highlight utility, stating "for most people mathematics means algebra and algebra means meaningless symbol manipulation" (Max) and "they just sort of memorize algorithms and that's useless" (Morgan).

To remedy these issues with how math is taught, the participants suggested that introductory math should teach particular content that aligns with other disciplines and mathematical thinking. For example, when asked what biology majors should take away from introductory math courses, Marley proposed a calculus/ordinary differential equations (ODE) series with biology applications and gave an example about the rate of metabolizing tea:

> Students should take sort of a Calculus I and a Calculus II in preparation for biology, but it should be a biology-based Calculus I, Calculus II.…it's about related rates, rates of change.…I've got my cup of tea here, and I've learned how the body eliminates drugs from the bloodstream.…It's a very simple ODE. And now I kind of now understand why is it I drink my tea, I drink tea in the morning, and then I need more tea later, next day, why? Well, because it's natural that there should be some sort of an exponential.

In addition to applications, the participants also said that introductory math courses should teach connected mathematical thinking. For instance, Mo claimed:

> We want to give them an idea of where those formulas come from because I think that gives a better understanding of how everything fits together. So it's not just covering the topics that they need, but it is also making sure that it's not just 'formula is given', but increase their understanding of the mathematics behind the things.

Together, participants claimed math courses should be specific to the student audience and focus on why content works.

Discussion

This study aimed to examine views of math, science, and biology by mathematicians and biologists as well as consider how well aligned (or not) the values, approaches to research, and material taught in introductory courses are in math and biology. To the first point, there was general agreement that biology is focused on the study of life, science uses the scientific method, and math is a tool for solving problems. However, mathematicians characterized math in terms of who does it (mathematicians) and in terms of studying patterns among (varied) objects as well as treating proof as central to activity, whereas biologists largely focused on numbers or expressed uncertainty. All participants also largely agreed that introductory math courses often teach disconnected procedures and not what is needed for other disciplines. They also largely agreed that the scientific method and content about living things were taught in introductory biology courses, though biologists elaborated on depth differences for majors and non-majors.

To the second aim and returning to our theoretical perspective (Laudan, 1984), we see relatively close alignment when we consider the axiology, methodology, and factual claims (as represented in courses) in biology as portrayed by mathematicians and biologists. While some values are in tension (i.e., science as a cross-disciplinary search for knowledge, science separated by jargon/in silos), we can see that both values are attended to and incorporated in the scientific method. In particular, hypotheses are free to change as science evolves and the questions asked are free to be informed by broad research teams, though individuals may have expertise in only portions of the question being asked. The emphasis on teaching the scientific method as well as all participants' certainty of what biology is seems to suggest relatively clear alignment between methods taught and accepted facts in biology. Finally, the emphasis on methodology rather than particular facts reveals connections between accepted facts and the value that science changes.

In contrast, math's axiology, methodology, and factual claims represented through course choices are harder to connect. If we attend only to mathematicians' views, the values of math being definite and of math being about relationships among objects harmonize with the methodology of deductive reasoning in an axiomatic system. However, teaching disconnected procedures does not create a foundation for proof-production. Instead, they at best relate to math's role as a (potentially not understood) tool for doing science. Biologists seemed to view math as a tool focused on numbers but had limited ideas of what mathematicians do beyond vague references to "math theory" and computation. Because math methodology is unknown to them, they cannot connect it to values or facts. However, the focus on math as a tool related to numbers potentially connects to the individual procedures or particular content taught in courses. Thus, while some aspects are connected in each viewpoint on math, there are also reasons for biologists to wonder what mathematicians do and for mathematicians to wonder why introductory courses are taught as they are.

These disconnections in math's values and introductory courses highlight problems for the math and math education communities to address. It seems that math courses are trying to serve populations that do not fully agree on what math is, thus serving no one well. If other members of the STEM community do not incorporate mathematicians' definition of math into their own definition or know "what mathematicians do", it is not reasonable to expect those in less contact with math to know what math is about or what mathematicians do either. One way to address this is to encourage mathematicians to clearly articulate what math is about to people outside the mathematical community so that their definition becomes more accepted. Another route might be for math departments to co-teach distinct courses with and for different STEM disciplines so that "applications" are relevant to all STEM majors and align with their needs, while math majors separately have opportunities to learn more about the mathematical community and know what their final courses will be about before it is too late to change majors.

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