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COLUMN: RETHINKING TECHNOLOGY & CREATIVITY IN THE 21ST CENTURY

Creativity in Mathematics and Beyond – Learning from Fields Medal Winners

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> For mathematicians, mathematics—like music, poetry, or painting—is a creative art. All these arts involve—and indeed require—a certain creative fire. They all strive to express truths that cannot be expressed in ordinary everyday language. And they all strive towards beauty — Manjul Bhargava (2014)
>
> Your personal life, your professional life, and your creative life are all intertwined — Skylar Grey

Every 4 years, the International Mathematical Union recognizes two to four individuals under the age of 40 for their achievements in mathematics. These awards, known as the Fields Medal, have often been described as the "mathematician's Nobel Prize" and serve both a form of peer-recognition of highly influential and creative mathematical work, as well as an encouragement of future achievement. In 2014, four individuals received this prestigious award.

The 2014 awardees also included some unique accomplishments. For instance, Maryam Mirzakhani became the first woman – as well as the first Iranian – to receive this accolade. And another winner, Artur Avila, was the first Latin American. Manjul Bhargava of Indian, Canadian, and American roots, and Austrian mathematician and Professor Martin Hairer were the other two winners. Each of them significantly advanced mathematics through their work in areas as specialized and diverse as dynamical systems theory, the geometry of numbers, stochastic partial differential equations, and the dynamical geometry of Reimann surfaces.

An award such as the Fields Medal is a recognition of *sustained creative effort* of the highest caliber in a challenging domain, making the recipients worthy of study for scholars interested in creativity. In doing so, we continue a long tradition in creativity research – going all the way back to Galton in the 19th century – of studying highly accomplished individuals to better understand the nature of the creative process. We must point out that the focus of creativity research has shifted over time, moving from an early dominant focus on genius, towards giftedness in the middle of the 20th century, to a more contemporary emphasis on originality of thought and work (Getzels 1987). Our work lies firmly in the latter category, in that we do not see these individuals as having "miraculous" creative powers but rather as having habits of mind that may be accessible to most if not all of us. In a previous article in this series (Mishra and Henriksen 2014). we had critiqued the perspective that saw creativity as something mysterious by arguing for a more prosaic perspective, or as we noted:

> Creativity is the end result of the manner in which human cognition works—and is available to all people. Finally, as with other human cognitive skills, there is a significant level of variability between individuals, and it can be learned and developed with practice. (p. 15)

Thus studying highly creative individuals, such as the Fields Medals winners, can provide useful cases of creative processes that can inform our thinking (even though their disciplinary work/knowledge – high-level mathematics – is not as easily accessible to us). Along these lines, Henriksen and Mishra 2015 studied the habits and approaches of highly

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creative teachers, and developed conclusions that could apply more broadly to all teachers seeking to become more creative in their teaching.

Creative Avocations

One of the important conclusions drawn from the study of highly creative teachers was that each of them spoke of their outside interests (their personal avocations) as being key to their creativity in their professional lives (Henriksen and Mishra 2015). This study showed many instances in which accomplished award-winning teachers used cross-curricular connections in their teaching of the subject matter. For example, these teachers frequently incorporated the arts or drama in teaching science. Every accomplished teacher in their study combined multiple personal avocations and interests, and gave credit to their outside hobbies as a core influence upon their professional creativity. These teachers used their personal passions and interests to ignite creativity and wonder in their teaching. They also used these personal avocations to shape the subject matter. This prefigures the question of whether this tendency (to apply outside interests and creative avocations to subject matter) applies to other disciplinary experts—such as, in mathematics.

This is where our Fields Medal winners come in to the story. These four individuals pushed the boundaries of their domain, in valuable and innovative ways as recognized by their peers. Thus the recognition of their creativity lies as much in their own work in the domain of mathematics as it does in the gatekeepers (the field) who selected them for the award (Csikszentmihalyi 1996). Thus they offer useful case studies of highly creative individuals and allow to see what attributes cut across their very diverse backgrounds and work. Prior to exploring these themes we provide brief bio-sketches of these four individuals.

Back to the Fields Medal Winners

Our approach was simple: for each of the four winners, we read and reviewed the official press releases, award descriptions, interviews, and biographical sketches released alongside the news of their awards. We did this to better understand how they both selected/approached the problems they worked on, their personal interests and avocations outside of mathematics, and the intersection of their work and creative thinking. Since Fields Medals winners become mini-celebrities around the time they win the awards, we were able to use online resources like *Math Union* and *Quanta Magazine* to develop insights into their professional and personal lives. We were interested in examples where they described the nature of their personal life and their hobbies outside of work. Below, we present brief profiles of these individuals.

Manjul Bhargava Creativity and varied interests were quite obvious in Manjul Bhargava's case. The influence of music in his mathematical profession speaks of a unique and inspiring relationship. Born in Canada, and rooted in India, Bhargava lived in the United States most of his life and now works as a professor at Princeton University. Born to a mathematician mother, Bhargava shared his earliest experiences of learning mathematics as a child not through his mathematician mother, but instead through the rhythms of his grandfather's teachings of Sanskrit poetry. Given his experiences, he finds a lot of similarities in mathematics and music, and any art for that matter. He explained these similarities using a common concept that drives mathematicians and artists equally: "the concept of trying to understand ourselves and the world around us," or perhaps, the search for truth and beauty. In Bhargava's case, both math and art drive him forward in more creative ways than commonly observed.

According to Bhargava, "one key way to solving any mathematical problem…is to think of it in a totally different way." Bhargava's big revelation came while he was playing with a Rubik's Cube. But, this is not the only place where he finds numbers and mathematics. According to his interview with Quanta Magazine:

> [N]umbers take positions in space – on the corners of a Rubik's Cube, or the two-dimensional layout of the Sanskrit alphabet, or a pile of oranges brought home from the supermarket. And they move through time, in the rhythms of a Sanskrit poem or a tabla drumming sequence. ("The Musical, Magical Number Theorist | Quanta Magazine" 2014)

Being an expert tabla (an Indian percussion instrument) player helps Manjul Bhargava's understanding of math. Playing the tabla, according to him, is quite similar to doing math. He often "turns to the tabla when he is stuck on a mathematical problem, and vice versa…Indian classical music – like number theory research – is largely improvisational" ("The Musical, Magical Number Theorist | Quanta Magazine" 2014). According to his interview to Quanta Magazine, "There's some problem-solving, but you're also trying to say something artistic…It's similar to math — you have to put together a sequence of ideas that enlightens you." In his interview to the Times of India, Bhargava makes clear cross-disciplinary connections to his personal creative avocations:

> I always found the three subjects—music, poetry, and mathematics—very similar. In fact, I find that I think about them all in very similar ways. In school, mathematics is generally grouped in the 'science' category.

> But for mathematicians, mathematics—like music, poetry, or painting—is a creative art. All these arts involve—and indeed require—a certain creative fire. They all strive to express truths that cannot be expressed in ordinary everyday language. And they all strive towards beauty. (Rajghatta 2014)

As an impressionable child, Bharagava saw mathematics everywhere. For instance, he sometimes multiplied large numbers for his mother, who had discovered this way to keep his high-spirited son still; or in another instance, he tried to calculate the formula behind piling a pyramid from oranges. In considering such background and examples of thinking without rigid disciplinary boundaries, it is clear that Manjul Bharagava's musical and mathematical journey is richly varied and cuts across the landscape of domains.

Maryam Mirzakhani A professor of mathematics at Stanford University, Maryam Mirzakhani – of Iranian origin – did not always want to become a mathematician. She loved reading novels and wanted to become a writer. As she got older, she realized she actually enjoyed mathematics, especially geometric structures. Unlike many mathematicians, she considers herself "slow" in process, because she enjoys ruminating over complicated and deep problems for years. She prefers solo time when she is not working. When she thinks about mathematical problems, she sits and visualizes.

She explained her process of working on a difficult math problem, as "you don't want to write down all the details – the process of drawing something helps you somehow to stay connected." Constantly drawing and sketching geometric structures on large sheets of paper, spread across the floor, Mirzakhani manifests a sense of wonder and deep play. In her interview, describing how she does mathematics through creating elaborate stories in her mind, she comments:

> There are different characters, and you are getting to know them better… Things evolve, and then you look back at a character, and it's completely different from your first impression. ("A Tenacious Explorer of Abstract Surfaces | Quanta Magazine" 2014)

Mirzakhani doodles her ideas on giant sheets of paper, which confuses her daughter, who thinks her mother is a painter. But this may not be farfetched because Mirzakhani noted how she enjoys crossing disciplinary boundaries and making connections, saying:

> I like crossing the imaginary boundaries people set up between different fields — it's very refreshing…there are lots of tools, and you don't know which one would work…It's about being optimistic and trying to connect things. ("A Tenacious Explorer of Abstract Surfaces | Quanta Magazine" 2014)

Mirzakhani's urge to go beyond the conventional boundaries of her field gives her the skill to make connections other mathematicians often miss. This is why even her colleagues feel that she tends to devise solutions to problems previously considered unapproachable. This skill is an integral part of who she is. Based on her personal experience, she does not believe that life is easy: "You have to ignore low-hanging fruit, which is a little tricky… I'm not sure if it's the best way of doing things, actually — you're torturing yourself along the way… Life isn't supposed to be easy."

In defining her most rewarding experiences as a mathematician, Mirzakhani tied back to the idea of wonder, just like Bhargava, stating:

> The most rewarding part is the "Aha" moment, the excitement of discovery and enjoyment of understanding something new – the feeling of being on top of a hill and having a clear view. But most of the time, doing mathematics for me is like being on a long hike with no trail and no end in sight. ("Maryam Mirzakhani" 2014)

Martin Hairer Martin Hairer is a professor of mathematics in The University of Warwick, Austria. Although he graduated with a PhD in physics, in his interview to Quanta magazine, he explained how he always knew "it was really a PhD in mathematics." Born to a mathematician father, his proclivity towards mathematics shaped how he saw the world from the very beginning. Even in his work as a student in physics, he tried to understand the math behind ideas. His disciplinary lens strongly influences how he perceives the world, as he believes that "no matter what you are doing, if you genuinely care about a problem, it is always in the back of your mind." In his case, like Bhargava and Mirzakhani, when he is not working on a mathematical problem, he is still mentally working a mathematical problem. He finds math in cooking, in music, and in everything he does. This perception led him to find "music in noisy equations," which became his masterpiece that brought him the Fields Medal.

Hairer, who is known for his "speed and creativity" among his colleagues, uses an approach "modeled on mathematical properties of 'wavelets'," which are used to encode information in JPEG and MP3 files. It is no surprise that Hairer is also the creator of an award-winning sound-editing program used by DJs, music producers, and gaming companies across the globe. His interviews reveal how he has always let music enter his profession, and vice versa. The transdisciplinary creativity in Hairer's case is obvious and plays a critical role in his professional and personal life. In fact, there are no boundaries between personal and professional lives for Hairer. This, according to him, stems from a "genuine curiosity" about problems, which is why he cannot leave math at work and "carries" it around with him wherever he goes. He explained:

> I think it is important to do genuinely curiosity-driven type of mathematics…It's only by being genuinely curious about a problem, genuinely interested in a problem, that you would be able to keep it in your head for sufficiently long time, or sort of think about it in a…focused way…to make some real progress. ("In Noisy Equations, One Who Heard Music | Quanta Magazine" 2014)

Artur Avila This "Brazilian wunderkind" and "globe-trotting dual citizen" of France and Brazil dislikes complications, and wishes to "calm things" down by simplifying them. He once declined an honorarium just to avoid the mental stress that is required to go over the complicated paperwork. He is afraid of the chaotic traffic in Paris, and fears that he will drift into thinking about mathematics while driving.

Although he prefers peace over chaos, he does not run away from it, he tries to simplify it. This calming attitude, along with the search for beauty – like Bhargava and Mirzakhani – is evident in his interviews. However, unlike Mirzakhani, his calming attitude does not mean that he is "slow" in pace. While Mirzakhani considered herself "slow" in approach and preferred solo activities in her free time, Avila is fast in approach, loves working with others, and travels the world in search of "attractive" problems.

Avila's attitude of finding calm in a chaotic world seeps in his profession as well. While in search of "attractive" problems, Avila stated that "Sometimes beauty is found in the mathematical statement and sometimes in the use of mathematical tools… When they mix together in an unexpected way, then it is something that I want to be working on." He is not the only one who identifies his search of "attractive" or beautiful yet complicated problems. His colleagues also agree that he can easily "demystify" complicated ideas, and make them look simple. This experience of working with him, for many of his colleagues, has changed their perception of mathematics ("A Brazilian Wunderkind Who Calms Chaos | Quanta Magazine" 2014).

Where most mathematicians connect to previous research to find solutions, Avila prefers talking to other people. He quickly visualizes mathematical problems and proposes solutions that most people need time to understand. He wants to help people and solve problems. According to his colleagues, he treats his mathematical genius as a hammer and looks for nails of problems to hammer. Professor of mathematics at Stony Brook, Mikhail Lyubich explained that:

> Part of Avila's strength is that he is capable of working in all these different areas and, in a sense, unifying them…He selects an area that looks interesting, finds the right fundamental problem to work on, then goes after it and is basically unstoppable. ("A Brazilian Wunderkind Who Calms Chaos | Quanta Magazine" 2014)

Several examples in these interviews suggested that Avila has a very different approach to looking at simplifying complex mathematical problems; which ties back to Manjul Bhargava's concept of search for truth and beauty. Like Bhargava, Mirzakhani, and Hairer, Avila also prefers to approach mathematical problems from a different perspective. In Avila's case, however, this perspective is driven by his general perspective towards life: the drive to calm chaos.

Three Themes: Personal Pursuits, Aesthetics, and Styles

Having looked at each of their profiles, what's common to these uncommonly impressive and creative mathematicians? As we look across their individual profiles and interviews, three things stand out. *First* is the manner in which each of these individuals saw mathematics everywhere. They did not define boundaries between their professional and personal lives or subject matters. Math is always a part of their lives; often shaped and influenced by their personal, creative interests. From playing musical instruments, to baking cookies, to doodling like a child, to playing with water on a beach, mathematics connects with everything else. These avocations emphasize the *transdisciplinary* nature of creativity we have emphasized earlier. In other words, "Creativity is not something that can be put into a box or pulled out only in specific moments when creative thinking is needed" (Henriksen 2011, p. 149). It is an "ongoing mindset" that is fostered by "openness to new ideas and willingness to try new things." These individuals often find it difficult to "turn off" their mindset, even when they are not at work. These four individuals saw their interests, hobbies or avocations as influencing and enriching their thinking within their professional disciplines (Root-Bernstein 1996, 1999, 2003).

Second, it is interesting to see the importance of the *aesthetic* in how each of these individuals approached their work. This was most evident in their use of words such as "a search for beauty" or "truth" in describing what they did. Fueled by aesthetic experiences, Bhargava and Avila searched for truth, beauty, calm, and peace through their work, while Mirzakhani and Hairer were driven by wonder – which made them all obsess over problems and solutions.

Third, this interplay between the personal and professional led to the development of unique *personal styles* in their approach to mathematics. Each mathematician here has a personal relationship to the domain, often shaped by their background, personal avocations, and their way of looking at the world, which in turn defined an identity as a mathematician. Their creative mindsets persist in their lives and everyday work. This informs how they see the world, and applies in their approach to mathematics and to other facets of life. It then becomes easier to see how things connect – to draw them out in large scale doodles, or to hear them in music, and see them in equations in their own unique ways.

In addition, these profiles point to the value of Csikszentmihalyi's framework where the individual, the domain, and the field each work together to define the creative act. The individual (each of these mathematicians) imbibes the contours of the domain, even while they seek to transform it. The field (their peers) negotiate and demand high quality work as defined by the domain—which in itself is transformed by the work of these individuals. We believe that the personal creative avocations and aesthetic aspirations drive creative mathematicians like Bhargava, Mirzakhani, Hairer, and Avila to a level where they excel creatively as individuals, as does their field, and the domain they work in. Creativity is where the individual, the domain, and the field operate in harmony (Csikszentmihalyi 1996).

Consequences for Teaching and Learning Mathematics

The view of mathematics described in the profiles of these four top-tier mathematicians differs greatly from the manner in which mathematics is taught in schools today. Mathematics today is akin to the drudgery of a forced march through enemy territory, brutal and slow, squeezing out any pleasure in the process (Brown et al. 2008; Eshun 2004). There is little space for fun and personal connections (Aiken 1979; Eshun 2004). or for seeing oneself as being a mathematician outside of the pages of the textbook, let alone for a sense of wonder or personal style. Students rarely if ever see themselves in the mathematics they are taught, and rarely if ever get a sense of the domain (Lave 1988). In this context the teacher becomes an important mediator between the domain and the gatekeeping functions played by the field. Of course, this view of learning in mathematics is an "artistic" way of approaching the domain, but as our profiles have indicated, it is consistent with how some of the best mathematicians in the field work. These profiles tell us that success in mathematics comes with passion and play, and from seeking connections across fields and disciplines. They provide a very different view of mathematics – as a living, artistic, organic structure, that mathematicians actively construct, in order to find truth and beauty in the world. We believe that this view of mathematics has significant implications for how we think of teaching and learning in this domain. It offers a novel and humanistic way of thinking about how to engage educators and learners in mathematical ideas.

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