Nonlinear Pathways into Mechanical Engineering

B. Reeja-Jayan

I believe my perpetually immigrant family is an example of the good that can come out of immigration. I was born in Kerala, India, and brought to the Emirate of Abu Dhabi in the United Arab Emirates (UAE) when I was just a baby. My father emigrated there over a decade before in pursuit of better economic prospects. A zoologist by training, he became an accountant to earn a living. Like other wives then, my mother stayed back in Kerala until my father could find a visa for us to join him: A terribly difficult feat at that time. My brother was born in UAE. My family returned to India when I started high school and has remained there ever since. I immigrated to the US, and my brother to Singapore and later Japan.

The country of my birth, India, is the world's largest democracy; the US is the oldest. Both Singapore and Japan are democracies. UAE has a ruling royal family. These international experiences shaped my family and me in every sense: The languages I speak, the religions I follow, the values I hold, my political views, the relationships I keep, the fears I live with, the ambitions that define me, and the (nonlinear) paths I have followed in my career. This chapter focuses on the last one—the many divergent paths that led me to an academic career in engineering in the US. To my readers, I wish to share with you the joy, risks, and hardships I experienced while taking these road(s) less travelled.

Path to Engineering

In my early days of school, I was not considered a "good" student. I think I existed and went through the daily motions without delighting or annoying anybody in particular. My earliest memory of an "accomplishment" was a memory test in the

B. Reeja-Jayan (✉)
Carnegie Mellon University, Pittsburgh, PA, USA
e-mail: bjayan@andrew.cmu.edu

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first grade. The teachers organized a large number of objects (from foods to toys) on a table, asked us to observe them, and then took us to another room where we had to list out as many items as we could remember from memory. I won that competition and received my first award. It felt good but not enough to motivate me any further in my daily learnings of math, science, language, and so on. I particularly did not like math (or maths as it was called then). As the years went by, my lowest score in this subject was even a zero. My mother tried to get me to sit down and study an hour every evening but I preferred to play with the neighborhood kids.

I loved watching cartoons on TV, though. They were in Arabic and this helped me learn the language and I did very well in Arabic classes (which were mandatory in schools in the UAE at the time). *Star Trek* (animation) reruns and Japanese sci-fi anime (all translated to run on TV in Arabic) were really the turning point which got me interested in science. These anime spanned everything from space exploration and extraterrestrials to robots and artificial intelligence. While these are all buzzwords and very real now, in the late 1980s they represented impossible dreams bordering on fantasy. I watched the 1987 movie *Robocop* so many times I knew the dialogues by heart. Research on such human–machine and other organic–inorganic hybrid systems are at the forefront of biology and materials engineering today, bringing the 8-year-old me of back then so much joy.

All the while, I continued to do poorly in school. One day after a particularly brutal parent–teacher conference in the sixth grade, my father had a serious talk with me. He told me how hard it was for him to afford the costs of sending my brother and me to school in UAE (there was a time I was almost kicked out for not making the fee payment deadline. An uncle stepped in and paid the fee). My father said he tried his best so we could have a good education and a future. He said he understood if I was not interested in school, but insisted that I persist and somehow pass the tenth grade exams. He said he is okay if I did not want to study further, as I could be married off early, which is typically what happens to girls in our family anyway.

I am not sure if it was the despair and disappointment I saw in my father or the mention of marriage, but something snapped inside me that day. I wanted to make my father proud of me, but more than that I wanted to have nothing to do with marriage. I saw all around me what that meant in our community. Women like my mother were not allowed to work after they had children. She diligently attended to our every need, spending 8 h or more in the kitchen, cooking every meal from scratch, cleaning and washing. Not to mention, I was an irresponsible child who never helped her in these chores. I have never seen my mother enjoy anything for herself. There is always a noticeable sadness in her and it makes me guilty every time we are together these days. A recent movie *The Great Indian Kitchen* does an accurate job in highlighting what is expected of married women hailing from Kerala, India; nothing fundamental has changed, even in 2021 [1]. Women in my family and the one I married into live this life.

After my sixth grade conversation with my father, I decided to take one chance to try and escape this cycle. I decided to study every day and review what was taught in each of my subjects the same day instead of my usual habit of opening my books the day before a test or exam. I thought this new resolve would last a week at the most, but that practice remains with me (in some form or the other) to this day. I ranked third among all students in the sixth grade classes in my school that year. The next year, I ranked second in seventh grade, first in eighth grade, and so on, until I ranked first among all students who took the tenth grade exams in the UAE.

Early Experiences in Engineering

My family moved back to Kerala, India, when I entered high school. I continued to do well in academics, especially in science subjects like chemistry and physics. When it was time to choose a path after graduation, I gravitated toward studying engineering as it seemed most in line with the science fiction (*Star Trek*, *Robocop*) that inspired me as a child. At the time, Kerala conducted entrance examinations to select students for engineering schools. Millions of students sit for these exams and the top 1000 or so get a free ride. The ranking determines the school and the branch of engineering you get to study. My rank was 594, and I was admitted to the University of Kerala in my hometown of Trivandrum/Thiruvananthapuram to study Electronics & Telecommunications Engineering, which is similar to what is considered Electrical & Computer Engineering (ECE) in the US. Solid state electronics was my favorite subject, which incidentally remains critical to the work I do today.

I did well in undergraduate engineering, and ranked first in the university upon graduation. My professors recommended I pursue graduate studies. Some of my peers applied to graduate schools in the US. I grew up on a healthy dose of American shows like *Star Trek*, which is why I became an engineer in the first place. An opportunity to study in the US was a dream. However, my family had fallen on financial hardships after my father left his job in UAE. I found work as a computer software programmer at a start-up to help my parents out and to support my brother's undergraduate studies. Nevertheless, I did not give up on my US dreams. I saved a little money from my salary each month toward paying for the GRE tests required to apply to the US schools. I studied on the weekends and did very well on the GREs, but my family found it inappropriate that I travel overseas without a husband. They refused to let me go alone to a country like the US (where we knew absolutely no one) unless I got married first. I knew what this meant. No husband was going let me hop on a plane and leave. Marriage tends to represent the expiration date for a woman's dreams in Kerala and most of India. In anger, I crumbled up my GRE scores and threw them into a box. I still wonder why I did not trash them. Perhaps a part of me held on to hope. The scores were valid for 5 years after all.

Two years later, I was selected (after a highly competitive process) to a scientist/engineer position at the Indian Space Research Organisation (ISRO) in the city of Bangalore/Bengaluru. ISRO surprised the world with their highly cost-effective mission to Mars in 2014 [2]. At ISRO, I got introduced to research that connects electromagnetism and materials. Spacecrafts in dangerous environments in space must be shielded to protect electronics and other subsystems from radiation and plasma. I got an opportunity to work with ultralight electromagnetic interference shielding materials based on sheets of amorphous metal alloys or metallic glasses. I currently research the fundamental origins of such electromagnetic field matter coupling behavior. This work has implications for applications from energy-efficient manufacturing to quantum electronics.

After 4 years of post-undergraduate work experience in various types of industries, I finally got my chance to pursue graduate studies. Ironically, this happened because I got married. My husband is the reason I am where I am in my career today. I had the equivalent of a tenured and permanent position at ISRO, we had bought a house in Bangalore, and were hoping to start a family. Friends and family told me it would be reckless to throw all this away and that this was the worst time to pursue my dreams. However, an offer to attend graduate school in the US (University of Texas at Austin, ECE) was not something I was about to turn down, no matter what sacrifices I had to make. On the day of my flight in August 2006, I woke up not knowing where/when I would next have a bed to sleep on. I was to fly from Bangalore, India, to Paris, France, and then Atlanta and finally into Austin, Texas. I made this journey alone. My husband, my biggest supporter, stayed behind and kept our enraged families at bay. Immigration rules prevented him from joining me, but he made it clear that I must pursue my dreams. I sold all my jewelry (wedding gifts from my parents) and used all our savings to finance my tuition and expenses for the first semester. I am grateful to The Ratan Tata Trust [3] for sponsoring my airfare to the US.

Like all international students, I, too, relied on the kindness of fellow students for accommodation, food, and generally learning the ropes. Two graduate students from India, Dr. Ashwini Gopal (ECE) and Dr. Chinmayi Krishnappa (Computer Science) remain my closest friends to this day. Their intelligence, scientific curiosity, sincerity, and accomplishments inspire me. Their support got me through very difficult times emotionally when I was lonely, separated from my family by oceans. My thrust area in ECE was called Plasma/Quantum Electronics and Optics. I was particularly interested in working at the intersection of quantum effects and nanomaterials. This was quite new in 2006, but is now a thriving scientific area. True to my nature to explore outside disciplinary boundaries, I started working in a department outside ECE. Professor Miguel Jose Yacaman in UT-Austin's Chemical Engineering department is a pioneer in atomic-scale studies of nanomaterials, particularly using transmission electron microscopy (TEM). He kindly allowed me to become a research assistant in his lab. Professor Selene Sepulveda, who was then a visiting postdoctoral researcher from Mexico, taught me everything I know about materials synthesis. I learned to synthesize and characterize nanostructures (particles, rods, wires) of materials like ZnO for broad applications in electronics, optics, and biology. I published my first peer-reviewed journal papers with Selene and the diverse group of brilliant researchers in this lab. Liquid phase materials synthesis, particularly under electromagnetic stimuli, is now at the core of my research program on energy and sustainability.

Doctoral Pursuits in Engineering

When I first saw atomic columns while imaging a gold nanoparticle specimen under the TEM, I felt very emotional. It was almost like finding a fundamental signature of God. I am a practicing Hindu, and our belief system is based on the principle of creation of matter (*Brahma*), conservation (*Vishnu*), and destruction (*Shiva*). This holy trinity is akin to the first law of Thermodynamics and connects all existence to the smallest of particles or atoms (anu). This experience with TEM had a profound impact on the rest of my academic journey. I decided I wanted to learn more about how materials form at the most fundamental level. This required learning Materials Science, which potentially meant changing majors. This is exactly what I did in 2008, when I completed my MS degree in ECE.

My future PhD adviser Professor Arumugam Manthiram offered me a position in his clean energy lab at UT-Austin. He suggested that I move disciplines to study Materials Science as part of the Texas Materials Institute (and I gladly accepted). This meant several additional years of course work and learning a whole new vocabulary (structure of materials, kinetics, phase transformation, electrochemistry, etc.). Once again, I was at a crossroads and I gladly took this fork in the road. I am so grateful I did this because Professor Manthiram's guidance continues to have a profound impact on me as a scientist and educator. In 2019, Professor Goodenough was one of three researchers awarded the Nobel Prize in Chemistry for inventing the lithium-ion battery that revolutionized portable electronics and is now set to save our planet by powering electric, pollution-free automobiles [4]. Professor Manthiram gave the Nobel lecture on the request of Professor Goodenough, who is now 98. The contributions made by both these extraordinary human beings to energy storage research is profound. For a nervous PhD student from India, seeing Professor Manthiram's passion for his work, scientific rigor and diligence, meticulous organization of his day-to-day activities, infallible work ethic (he used to be in his office every day around 6 am), and passion for teaching and mentoring inspired the way in which I advise my students now.

Professor Manthiram believed in me from the very beginning. So much so that as a first-year PhD student he put me in charge of setting up an energy-harnessing (solar photovoltaic) research thrust in his group. Step 1 of my PhD thesis was to find a broom; clean out an old furnace lab; and carve out space for a workbench, glovebox, and a solar simulator. Together with a dedicated team of undergraduate and MS students I was able to get this project going. We eventually discovered a process for low-temperature synthesis of ceramic oxide thin films using microwaves, which found use in the electron transport layer of flexible polymer–ceramic hybrid solar cells [5]. Along with materials for solar cells, I also developed coatings to passivate the reactive electrode–electrolyte interfaces inside lithium-ion batteries. NASA funded these fast-charging batteries, for use in spacesuits worn by astronauts during extravehicular activities [6, 7].

My husband had joined me in the US by this time and just as things were starting to feel well again, I suddenly got very sick. It began as stomach problems, which got worse after I got a stomach bug during a 2011 trip to India to renew my F1 student visa. One night it got so bad I had to go to the ER with severe vomiting and diarrhea preventing me from even keeping down water. Doctors could not find anything wrong and sent me home to rest. As the weeks went by, I felt better but started shedding weight, I lost 40 pounds in a span of months. When tests revealed nothing wrong with me, I was sent to a dietician who suggested I might be bulimic. Even family members and several acquaintances also thought I was doing this to myself. It was a dark and miserable time and I threw myself into my research work to escape it all. I read scores of books on all sorts of topics. I also read a lot about the interaction between microwaves and matter, and how these effects can help synthesize new materials with interesting properties. Years later, this idea would become the scientific nucleus for my own lab. I have this time of sickness to thank for it. If I had not fallen ill, I would not have had the time to pause, reflect, and think.

Sometime in 2012 my weight started dipping again and reached as low as 85 lb. as shown in Fig. 1. Fearing cardiac damage, I was subjected to a battery of tests to figure out what was wrong. Celiac disease was suggested (based on my gastrointestinal symptoms). Celiac is an autoimmune condition in which the ingestion of food containing the protein gluten (found in wheat, barley, rye, etc.) triggers the immune system to attack the gastrointestinal tract. Over the years this attack damages the ability of the intestinal villi to absorb nutrients from food, resulting in undiagnosed patients literally wasting away (as I was) [8]. However, testing blood markers for Celiac disease was still new and insurance would not approve the highly sensitive

Fig. 1 Sudden and excessive weight loss is a symptom of undiagnosed Celiac disease. Coupled with the stresses of graduate school, my weight dropped to dangerously low levels and I was at a very low point in my life in 2011–2012

Celiac test suggested by my doctor. I was not a Caucasian and it is widely (and wrongly) presumed that Celiac disease does not affect people of color. Months later I got the test conducted, and tested positive for Celiac disease in the summer of 2012. I continue to suffer from Celiac consequences even now. I joke that I have visited ERs in all the major tourist places in the US. I even went to the one in Napa Valley during a vacation. The reason for all these ER admits is that it is almost impossible to maintain a gluten-free diet in our modern world. Gluten is the second most widely used material in the food industry (after sugar). I was particularly sensitive to even trace levels, which made it very hard for my intestines to heal.

When I showed up for my PhD defense in May 2012, many members of my dissertation committee did not recognize me because of how frail I had become. They were extremely concerned. But I soldiered on and passed. I stayed back in UT-Austin as a Postdoctoral Research Fellow in Professor Manthiram's lab. I am grateful for this time, which gave me space to heal and plan for my future. In academics, taking time off the perpetual treadmill is usually frowned upon. Once again, this time was critical to the next step in my career.

My husband and I wanted to start a family but decided to wait due to my ongoing health issues and uncertainties with our immigration status (neither of us had a green card or permanent resident status yet). Disapproval from family and my own awareness of the fertility time limit facing me as a woman were constant sources of worry. Years later as an early career faculty, I would be faced with these questions again: "*Is this the right time to have a baby? What happens if I wait too long?*" This is a dilemma faced by all women pursuing growth in their careers.

MIT Bound

In 2013, I started applying to jobs in industry (becoming a faculty member was the farthest idea from my mind then. I simply believed I was not good enough for such a job). After a disastrous industry job interview, I decided to also apply for postdoctoral research positions at universities. I had taken up a part-time position as the Associate Technical Editor for the Materials Research Society (MRS)'s flagship journal *MRS Bulletin*. *MRS* is the largest international society for materials scientists. I edited journal articles in the *Bulletin* for their technical content. While editing one such article, I learned about the work done by Professor Karen Gleason's lab at MIT Chemical Engineering on paper-based photovoltaics, sensors, and other devices. It was a long shot but I was so excited that I curbed my fear and wrote to her. I immediately got a reply asking if we could meet. My husband bought me air tickets to fly to Boston and meet Professor Gleason. Years later, Professor Gleason said she liked my "chutzpah" for just showing up in her office. That—along with my background in lithium-ion battery work, polymers, and devices—made her offer me a position in her lab. For me, this opportunity to train at MIT was unbelievable and as far away from the dreams of the shy immigrant girl who consistently felt she was not good enough to be an engineer.

In Chemical Engineering, I learned a whole new discipline yet again, this time about reactor design, transport phenomena, and process engineering. These topics helped form the foundation of the ceramic manufacturing thrust in my lab. Professor Gleason was the first female professor with whom I have worked. She is my role model. She taught me to be confident, to believe in the quality of my work, to stop second-guessing myself. Her scientific prowess (she discovered the vapor-phase polymerization process using chemical vapor deposition (CVD) and developed it into a commercial technology now used internationally); her engineering acumen and all-around optimism and confidence is so infectious. As the first woman to get tenure in MIT Chemical Engineering, Professor Gleason has experienced her share of challenges, and she works tirelessly to mentor and support her students and post-docs. She is especially sensitive to the challenges faced by her female trainees. She once told me that every time I come to her with data, I spend the first 5 min berating myself for the things I did not do, before finally getting to the data from the experiment I actually ran. As women, we tend to assume intellectual modesty is the "proper" thing to do, but it can have consequences to succeed in the self-promoting world of academia. I still suffer from imposter syndrome [9]; it never goes away. But over time I learned to consciously tame it. Working with Professor Gleason was instrumental to this change in me.

While my PhD focused on ceramic and polymer–ceramic hybrids, my postdoctoral work at MIT went deeper into polymers, particularly CVD polymerization which allows us to precisely engineer complex surfaces with a variety of functionalities. I focused on the applications of these conformal coatings in 3D microbatteries, a way of miniaturizing energy storage. These days we talk a lot about scaling up batteries for electric vehicles, but going the other way to scale down batteries is still hard.

I collaborated across departments and even institutes on campus like the Institute for Soldier Nanotechnology [10]. A frequent hangout for me was with Dr. Andrea Mershin's team at the Center for Bits and Atoms [11], a wonderous place where engineering intersects with space exploration, movie making (*Star Trek* director J. J. Abrams hangs out in the building), building artificial life and intelligence, and other extraordinary pursuits. These experiences helped me dream big, I mean *really* big, when it became time to contemplate my next steps.

Professor Gleason was clear that I should apply for tenure-track jobs at R1 universities. She connected me to other mentors at MIT like Professor Hadley Sikes, who coached me through the application, interview, seminar, chalk–talk marathon of around 10 faculty job interviews. A challenge for me was managing Celiac disease. Long days on the road and eating out at restaurants were dangerous for me due to chances of inadvertent gluten exposure. Almost all my hosts accommodated my requests and made every attempt, but sometimes things just went wrong. I gave one job talk while being very sick (my faculty host kindly pointed out that I must rest before the next event on my agenda). One of the ideas I was pitching as part of my independent research was to engineer polymer-based sensors to detect gluten. This personally inspired research goal was highly appreciated in the interviews and this hobby of a project eventually became a funded research thrust in my lab, graduating my second PhD student, Dr. Phil Smith.

Starting My Own Lab @CMU

In 2015, when I started at Carnegie Mellon University (CMU) as a faculty in Mechanical Engineering, I was a lot older than other starting faculty in my cohort, mainly on account of the extra time I spent to get there. I could feel the weight of all these experiences. Indeed, the Dean of the college told me during our first meeting that my degrees and diverse experiences made me a candidate that stood out in the search that year. An academic career is stressful, period. There is no way to sugar-coat this. My autoimmune condition is triggered by gluten, but my physicians told me that stress accelerates these responses.

However, I also got to do some extraordinarily fun things. I had heard about work being done in game-based learning. This, along with my own early interest in video games (I played *Atari* games a lot), inspired me to develop a course where I used the game *Minecraft* to teach materials science to mechanical engineering students. Minecraft is a game where you can start with simple cube (blocks) and build anything from a Tesla Gigafactory to a space station. Students in my course can browse through rooms that teach them about Bravais lattices, crystal structures, defects, etc., as shown in Fig. 2, as well as build their own projects dealing with materials processing (plastic recycling, brick-making factory). Experiences from my first job as a computer programmer helped me embark on this project, which I believe can one day replace or augment traditional pedagogical methods. This project [12] was made possible by the Wimmer and Struminger Fellowships, the 2018 National Science Foundation CAREER award, and most importantly by my student Michael Oden working with a dedicated team of CMU undergraduate students.

An overarching goal of research in my lab (J-Lab) [13] is to use electric and electromagnetic fields for engineering energy-efficient processes to synthesize materials. When we succeed, our work can impact the way we produce ceramic materials that find applications in energy devices, sensors, electronics in areas as diverse as environment monitoring, transportation, aerospace, telecommunications, and healthcare [14]. Currently, producing these materials requires extremely high temperatures, making these processes highly energy intensive. We engineer reactor systems that allow us to use synchrotron X-rays to monitor the growth of materials, under electromagnetic fields (microwaves). Our highly multidisciplinary research merges together insights in electromagnetics, engineering physics, and materials chemistry. Events along my personal journey were often trigger points that helped me to navigate the map of these diverse disciplines and form connections that became invaluable to my career. My first PhD student, Dr. Nathan Nakamura (now a National Research Council (NRC) Postdoctoral fellow at National Institute of Standards and Technology (NIST)) collected the very first experimental evidence that microwaves change the atomic-scale structure of metal oxides. He took a

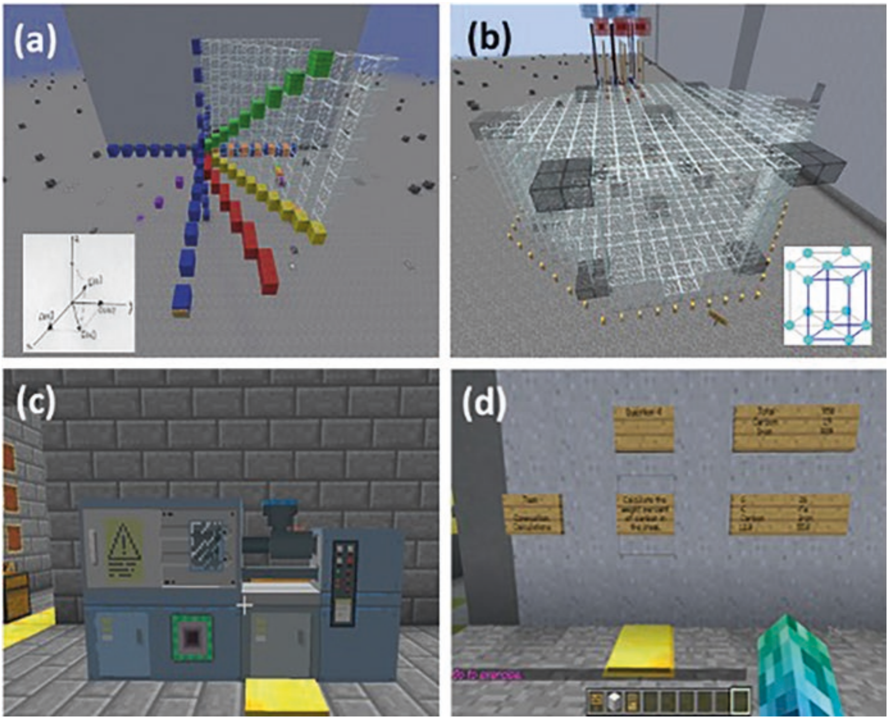

Fig. 2 Video games and science fiction inspired me to become a scientist and an engineer. Teaching engineering using games like Minecraft is a dream come true to me. This picture shows examples of various learning modules set up in my course to teach processing–structure–property relationships in materials

chance on me as a new faculty with a strange idea. My PhD student, Dr. Laisuo Su, was able to apply our techniques to develop faster charging lithium-ion batteries. He is now a Postdoctoral fellow in Professor Manthiram's lab. Laisuo starting his post-doctoral work in my old lab was a proud and emotional moment for me. I am grateful to all the undergraduate and graduate students (not enough space to name them all here) who continue to push hard so that our lab can pursue and realize seemingly impossible feats.

In 2019, my husband and I had a son, as shown in Fig. 3. Mine was a complicated pregnancy with many ER visits, ending in an emergency C-section, and our baby spending time in the NICU. It was a difficult time but we are grateful and lucky to have him. Coming back to work a few months after was hard. My parents flew from India to help me and I am ever so grateful for their support when I was so vulnerable. Then COVID-19 hit and my parents could not travel back home. Cooped up indoors during this strange time brought back old arguments and resentments but I am glad we got this time together. We agreed to respect each other's choices and perspectives, and to be thankful that we have each other to love.

Fig. 3 Our first child and my best friend is a Hungarian Puli Tiberius (Tubby) who is named after the father of Captain James T. Kirk (Captain of the Starship Enterprise in *Star Trek*). This was the moment where my husband Aji introduced our newborn baby to Tubby

Science Fiction Dreams

In true journal fashion, Fig. 4 summarizes all the forks in the road that I took to become a faculty member in a top Mechanical Engineering program. I don't even hold a Mechanical Engineering degree! Could I have planned such a nonlinear trajectory for myself? I believe not. Did I have mentors? Yes, definitely. Was it luck? Yes, partly. But it was also a philosophy. Did it always work? Definitely not. At each of these transitions in my life, the decision-making had nuances and sometimes I took one fork, followed it, failed, and went back to the road to take the other fork. Along the way, also came the challenges of immigrant life, family pressures, and health struggles. Failure is especially hard when you come from years of imposter syndrome. But you can push back through hard work, determination, continuous improvement, and never giving up. This philosophy that defines my journey is the one piece of me I wish to leave with my students.

In all our endeavors, it is important to keep dreaming. For me the magic comes from science fiction. Through our electromagnetic field–assisted synthesis work, we may one day make a *Star Trek*–style replicator that can assemble any material and tailor its properties to our liking. I am so thrilled to be working with colleagues who are pushing the boundaries of human–machine interfaces (something that was fantasy when I watched *Robocop* in 1987). Materials play a key role in these advancements. I am so excited that a part of my dreams are coming true already: Through

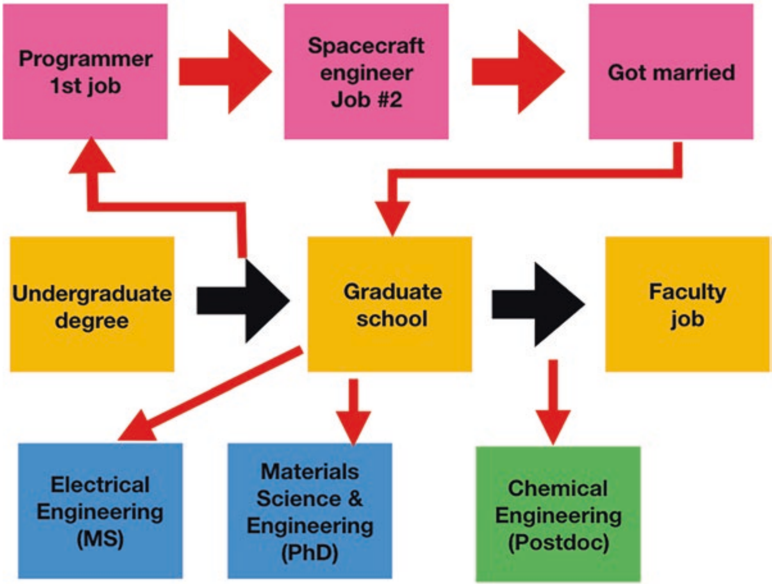

Fig. 4 The black arrows and yellow boxes represent what is typically considered a traditional path to a faculty position in Mechanical Engineering. The red arrows and other color boxes represent my nonlinear path

our collaborations on *Terminator*-style liquid metal–based stretchable batteries [15] and using machine learning for autonomous discovery in science and engineering [16].

When this pandemic ends, I hope we can all start to dream again and search for, find, and journey down strange new roads we previously might not have considered. These *roads not taken* may make all the difference in our new post COVID world. As the Robert Frost poem goes [17]:

I shall be telling this with a sigh.
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—.
I took the one less traveled by,
And that has made all the difference.

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B. Reeja-Jayan is an Associate Professor in Mechanical Engineering at Carnegie Mellon University. She also holds courtesy appointments in Materials Science and Engineering, Chemical Engineering, and Electrical & Computer Engineering departments. She is also a Faculty Fellow of the Scott Institute for Energy Innovation and Dean's Early Career Fellow in Engineering. Her multidisciplinary lab explores ways by which electromagnetic fields can synthesize materials hitherto unavailable to conventional synthesis routes. These low temperature processed materials directly grow on flexible, lightweight substrates, enabling structurally integrated energy and sensing. Dr. Jayan is a strong believer in game based learning methodologies that she uses extensively in her undergraduate and graduate engineering courses. Dr. Jayan is a recipient of the 2018 National Science Foundation CAREER Award, 2017 Army Research Office (ARO) Young Investigator Award, 2016 Air Force Office of Scientific Research (AFOSR) Young Investigator Award, the George Tallman Ladd Research Award, the Donald L. and Rhonda Struminger Faculty Fellowship, the Berkman Faculty Development Fund, and Pittsburgh Magazine's 40 Under 40 Award. Her research is also funded by the Department of Energy (DOE), Defense Advanced Research Project Agency (DARPA), and by private sponsors.

Originally, from Kerala, India, Dr. Jayan now lives in Pittsburgh, PA with her husband Aji, her toddler Neil, and her puppy Tubby.