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Management Mathematics: The Audacity of BOPE[1]

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Can mathematical research from a business school professor that is published in academic journals also substantially improve actual industrial practice in global supply chains? Yes. Can mathematics and operations management help improve fairness in access to organ transplants? Yes, again. Can mathematics developed for business applications facilitate the development of new types of quantum hardware? Also, yes. I have three main messages in this invited essay: (1) free yourself from self-imposed constraints and explore a wider range of new problems and arcane mathematics; (2) be bold and imaginative in developing novel solutions and (3) implement your ideas in practice, scaling them with a channel partner.

Keywords: Supply Chains; Healthcare; Quantum; Software Entrepreneurship; Social Enterprise.

1. The importance of being audacious

What propels my professional career is a preoccupation with *conceiving and implementing novelty* as in through my *social enterprise*, OrganJet (Ata *et al.,* 2016); see Table 1. I am as attracted to identifying new problems to tackle as to employing new mathematical methodologies that can be (and frequently actually are) implemented in practice, at scale, with measurable results. This invited essay showcases the major themes of my professional career over the last three decades: novelty in methodology, deliberate problem selection, implementing solutions in practice and identifying mechanisms (and associated channel partners) to scale such implementations. I have been inspired by Emerson (1841):

There is no outside, no inclosing wall, no circumference to us. The only sin is limitation.

2. Novelty matrix

Figure 1 lays out some examples in the familiar 2x2 box framework, with *problem choice* and *solution methodology* as the two axes. The problem choice can be *canonical* or *contemporary* (which I will take as a synonym for novel); the solution method can be *classical* or *novel*. In this section, I will highlight some of my activities in the three boxes where there is at least one source of novelty.

[1]Business Optimizing Professor–Entrepreneur.

TABLE 1 *OrganJet: a liver transplant patient near Boston is transported to Mayo Clinic (in Rochester, Minnesota), on-demand, in under 5 h*

Suburb outside Boston	
00:00.	Patient receives call from *Mayo Clinic* in Rochester (MN).
00:01.	Calls *OrganJet.*
01:36.	Wheels up, on *Learjet 45* [Range 2250 miles at Mach 0.8].
04:11.	Lands. Limo pickup.
04:46.	Reaches Mayo.

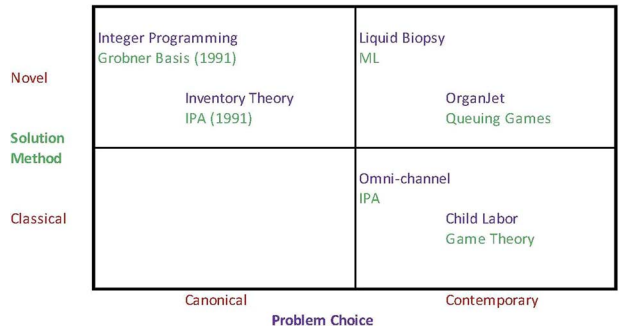

FIG. 1. Novelty matrix.

2.1 *Canonical problem choice, novel solution method*

2.1.1 *Serial production lines, sample path comparisons.* I first studied serial production lines (Tayur, 1993b), which was by then a fairly well-studied problem, but was done so almost entirely through Markovian models or via simulation. Differently, I tackled this *canonical problem* using sample path methods and stochastic comparisons. I found structural results that hold in good generality, and help in significantly reducing the computational burden when designing actual production lines. Additionally, it was particularly amusing that the many numerical studies and simulations conducted through Markovian models in published papers were actually done on provably non-optimal solutions! Some years later, I helped implement a Kanban system at GE (Tayur, 2000).

2.1.2 *Integer programming, algebraic geometry.* Around that time, I was also quite enamoured by Algebraic Geometry and Grobner basis, concepts (well) outside operations research, and found that it was possible to study integer programmes, using ideas from polynomial ideals (Tayur *et al.,* 1995), in two different ways (Bertsimas *et al.,* 2000), in fact! So, here was another example of coming up with methodological innovations for the most fundamental of hard mathematical programming problems, integer programming, and conceiving two different approaches, which were not incremental to, nor intimated by, the mainstream methods (such as Branch and Bound).

2.1.3 *Multi-stage production-inventory models, IPA.* Continuing to focus on canonical problems, in my summer internship at IBM Somers, I had the good fortune to be exposed to real-world issues in what is now called *supply chain management*: planning global inventories inside a multi-national enterprise,

TABLE 2 *Various applications of IPA*

Topic	**Infinitesimal perturbation analysis**
Multi-echelon inventory	Glasserman & Tayur (1995)
Non-stationary demand	Kapuscinski & Tayur (1998)
Lead time quotation	Kapuscinski & Tayur (1998)
Postponement	Swaminathan & Tayur (1998)
Cyclic schedule	Anupindi & Tayur (1998)
Value of information	Gavirneni et al. (1999)
Rapid response SC	Rao et al. (2000)
Re-entrant flow	Bispo & Tayur (2001)
Risk sharing in SC	Scheller-Wolf & Tayur (2009)
Omni-channel	Jia *et al.* (2021)

using multi-stage, discrete-time, stochastic production inventory models. I immediately realized that, for any model that provides useful outputs, the production *capacity* (Tayur, 1993a) needs to be constrained, clearly violating the celebrated Clark–Scarf model. Through sample path derivatives obtained via infinitesimal perturbation analysis (IPA) (Glasserman & Tayur, 1995), with few assumptions (especially of stationarity or having specific, distributional forms of demand, or even limited to the topology of pure serial or pure assembly or pure distribution networks), this novel methodological advance allowed, for the first time since the origins of modern inventory theory (in the 1950s), to actually provide industries with sophisticated solutions that could be implemented at scale (Tayur, 2013) with vastly superior performance measured on business metrics (service levels, working capital investment), consequential to both the income statement and the balance sheet (thereby increasing shareholder value and stock price, in publicly traded companies (Troyer *et al.,* 2005)), in addition to satisfying academic requirements (Glasserman & Tayur, 1994) (such as being unbiased and guaranteeing convergence).

IPA has wide-ranging applications (Table 2) including periodic demand (Kapuściński & Tayur, 1998), quoting lead times (Kapuscinski & Tayur, 1998), stochastic cyclic scheduling (Anupindi & Tayur, 1998), understanding the value of information sharing (Gavirneni *et al.,* 1999), re-entrant flow shops (semi-conductor manufacturing) (Bispo & Tayur, 2001) and risk sharing in global supply chains (Scheller-Wolf & Tayur, 2009).

2.2 *Contemporary problem, classical solution method: private jets, MILP*

I also had (in 1994) the opportunity of working on a *new business model* (Keskinocak & Tayur, 1998), fractional jets, which had to be scheduled. The methodology and framework we used was somewhat routine: Mixed Integer-Linear Programming (MILP). The important aspect, beyond having identified a new problem, was that our solution was implemented, and was crucial for the effective daily operation of the business. Since then, other such companies have developed similar algorithms and added crew scheduling (Yang *et al.,* 2008) and use it for ongoing operations. Other examples of MILP models that have been implemented in practice include Bundling and Pricing (Shunko *et al.,* 2018) at Caterpillar, Product Portfolio Optimization (Yunes et al. (2007) at Deere, Production Planning (Mehrotra *et al.,* 2011) at ConAgra Foods and Scheduling Advertisements in Video Games (Turner *et al.,* 2011) at Microsoft; see Table 3.

TABLE 3 *Various implementations of MILP (and extensions)*

Application area	MILP model publication
Time-shared jet aircraft	Keskinocak & Tayur (1998) Yang *et al.* (2008)
Bundling and pricing	Shunko *et al.* (2018)
Product portfolio optimization	Yunes *et al.* (2007)
Production planning	Mehrotra *et al.* (2011)
Ads in video games	Turner *et al.* (2011)

2.3 *Contemporary problems, novel method*

2.3.1 *Vanilla boxes and rapid-response supply chain, IPA.* The other *new* problem that attracted my attention was in managing broader product variety through delayed differentiation, also called *postponement*, using *vanilla boxes* (Swaminathan & Tayur, 1998). This was formulated as a two-stage, stochastic program with recourse. Using (the then recently developed) IPA as the computational methodology, IBM applied this to its PC line of business, in Raleigh, North Carolina (to compete against Dell, who had just invented a new method of delivering products to consumers, now called the *direct to consumer* model), saving them over $600 million annually.

What made IPA (and my academic research) widely known to business executives was a *Fortune* article (Seikman, 2000) that described our implementation at Caterpillar (Rao *et al.,* 2000), which was another new, that is, contemporary, problem of designing a rapid-response supply chain for a new line of (small construction) products, such as Skid-Steel Loader (SSL) and Compact Wheel Excavator (CWL) (to compete against an entrenched market leader, Ingersoll-Rand, that makes Bobcats). To this day, this excerpt brings me great joy:

> Among the techniques the Carnegie-Mellon group used to attack this complex problem was the so-called infinitesimal perturbation analysis, for which no complete explanation is possible for the faint-hearted or mathematically disadvantaged.
>
> . . . the Carnegie-Mellon solutions are not what Cat would have come up with on its own. A couple of special tool-distribution centres, which the company had planned to build, were found unnecessary. Just as important, the response time in the system was sufficiently fast that the inventories that the dealers would have to carry were not high enough to require a subsidy from Caterpillar. [Carnegie Mellon] gave us the highest response, lowest cost, lowest inventory [solution]...

2.3.2 *Alpha optimal combination, quantum-inspired algorithms.* Were the algebraic geometry algorithms developed for integer programmes implemented anywhere? Not at that time, but, I have now—25 years later!—repurposed them into a quantum-inspired algorithm (Sodhi & Tayur, 2022), and implemented it at QuantBot Technologies, a multi-billion dollar Hedge Fund Manager, in a contemporary problem, Alpha Optimal Combination. Here *alphas*, representing positive market signals that are noisy and correlated, derived daily from various machine-learning (ML) algorithms, from various research sub-groups, need to be combined optimally (by the Chief Investment Officer, CIO) to yield the best total daily return subject to several constraints on risk.

TABLE 4 *Academic Prizes. CHOM: College of Healthcare Operations Management of POM Society. Pierskalla Award for Best Paper, from INFORMS Healthcare Application Society. MSOM Best Paper Award, from MSOM Society. PSOR: Public Sector Operations Research, from INFORMS*

Topic	Mathematics	First prize
Overtesting	Queuing Games	CHOM (2012)
OrganJet	Queuing Games	Pierskalla (2015)
Liquid biopsy	ML	Pierskalla (2021)
Combating child labour	Game Theory	MSOM (2022)
Split liver transplant	Fluid Model	PSOR (2022)

2.4 *Frivolous-gravitas Spectrum*

Recently, I had the opportunity to work on omni-channel fulfillment (Jia *et al.,* 2021), a contemporary issue in retail operations, using what I now call a classical method: IPA. This work was done in collaboration with a startup called Onera Commerce (co-founded by a CMU alum and acquired by Tools Group), whose clients include Dick's Sporting Goods and Saks Fifth Avenue. Likewise, motivated by Rent-the-Runway (IPO in 2021), a new business model that rents out high-end fashion, we analysed their operations (Slaugh *et al.,* 2016) using sample path comparisons!

Contemporary problems analysed with novel solution methods, in particular ML approaches, include liquid biopsy (through adaptive sequential hypothesis testing) (Gan *et al.,* 2021) and split liver transplantation (through multi-armed bandits) (Tang *et al.,* 2021).

Why always be so serious? In *Frivolous-Gravitas* (FG) spectrum, video games (Turner *et al.,* 2011) may be considered discretionary and frivolous (although gaming is a big business), in contrast to organ transplantation and cancer genomics, which are usually thought of as having gravitas and essential. Our dynamic scheduling of advertisements in video games was done in collaboration with Massive Incorporated, a startup that was acquired by Microsoft (reportedly for $400 million): Would you consider that frivolous? Private Jets can be likewise considered discretionary; but, making them affordable and widely available for life-saving transplants? Audacious, is not it?

3. The engineer as an entrepreneur

Identifying new problems: yes, it is fun. Formulating them creatively and solving them innovatively is even more fun. Publishing them in prestigious journals and winning academic awards (Table 4)—sure, why not? Editing research–oriented books in supply chain management (Tayur *et al.,* 1999) and healthcare (Dai & Tayur, 2018) for the academic community? Yes, it is important.

What is even more enjoyable and fulfilling is having companies actually implement your recommendations/algorithms, and being compensated handsomely (Camm & Tayur, 2010), proportionally to, even half of, the value that your implementation created (Tardif *et al.,* 2010). This has been the story of my research career over and over again, whether in manufacturing, in supply chains, in private jets or in video games.

3.1 *Software entrepreneurship*

How to go from *one-off* commercial projects and create a repeatable model? How to change industrial practice worldwide? One is to partner with a (major) consulting firm; for instance, I have a good

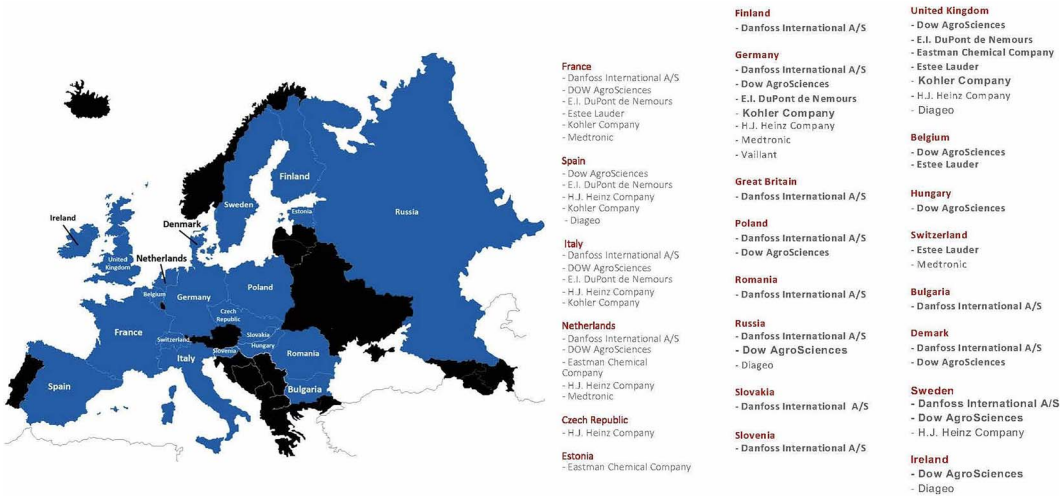

FIG. 2. Some examples of SmartOps EIO in Europe.

long-term relationship with McKinsey & Company. This, however, is still not very scalable, nor is it particularly satisfying to me. A second approach is to be a *software entrepreneur*, which I was, as Founder and CEO of *SmartOps Corporation* (acquired by SAP), and when I created the market for Enterprise Inventory Optimization (EIO) software. Over 700 global companies (Caterpillar, for example (Keene *et al.,* 2006)), across a variety of industries, in over 50 countries (see some examples in Europe, Fig. 2), use EIO on an ongoing manner, connected to their enterprise information technology (IT) backbone.

3.2 *Social entrepreneurship*

I opened this essay with *OrganJet*, my second entrepreneurial venture (Roth, 2012), a social enterprise that focuses on democratizing access to transplants by providing on-demand and affordable access to private jets (see Fig. 3). How to analyse the equilibrium consequences of this innovation? Each transplant centre can be considered as an over-crowded queue with abandonment, and multiple listing as selfish routing in a network of such queues. The equilibrium is studied through fusing game theory with queuing: rational queues or queuing games (a mathematical technique also used in studying overtesting in healthcare) (Dai *et al.,* 2016). Analysis using real data shows that OrganJet increases the number of transplants, through an increase in organs used (and by reducing the discards) and transplants the ones in need in a timely manner, thus reducing geographic inequity and the number of deaths on the waiting list. This is perhaps the most dramatic demonstration of Rawlsian concept (Rawls, 1985) of fairness, made possible through matching demand with supply using private jets on-demand. For over 12 years, OrganJet has provided hundreds of people an opportunity to obtain transplants earlier and has made their lives better. I am very happy to be contributing to *Market Design* (Roth, 2002) by re-imagining the US Transplant System (Table 5).

3.3 *Scaling: matching content with channel*

I think a lot about how the *content* I am developing can be scaled, that is, what is the *channel* for its widespread dissemination beyond publications (Table 6)?

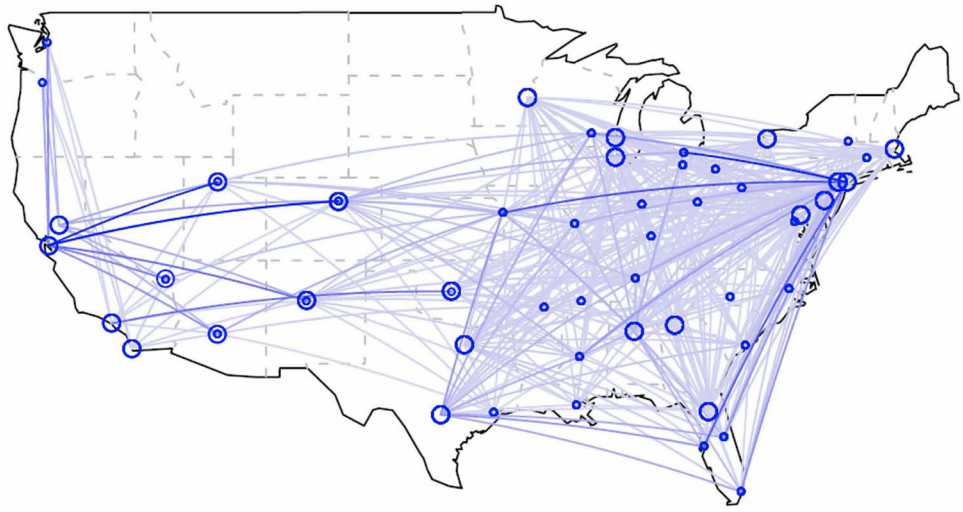

FIG. 3. OrganJet: flight paths due to multiple-listing.

TABLE 5 *Market design: re-imagining the US Transplant System*

Patient/ Society issue	**Market design solutions requiring no reforms**	**Proposed reform**
Geographic disparity	OrganJet	
Size/ Gender inequity	Split liver transplantation	Exception points by height
Supply shortage	Nudge Videos	

TABLE 6 *Matching content with channel*

Content	**Channel**	**Year**
Supply Chain Analytics/Entrepreneurship	McKinsey & Company	1998
SmartOps Enterprise Inventory Optimization (EIO)	SAP	2004
OrganJet & GuadianWings	Harvard	2011
Nudge Video for NOK consent	White House	2016
Maximally Inverse Thinking	WEF /HKS	2017
Quantum Integer Programming (QuIP)	NASA/USRA	2018
Unconventional Computing	TED	2020

Beyond OrganJet (which is a Case Study (Battilana & Weber, 2013), as is SmartOps (Wilcox & Yemen, 2011), both distributed by Harvard), I am most proud of the *Nudge Videos* that are being used at many Organ Procurement Organizations (OPOs) to increase second-person consent from next-of-kin (NOK) (Kush & Tayur, 2022), an initiative that was highlighted by the Obama White House in 2016, and is now in use at various OPOs. Both OrganJet and Nudge Videos are examples of *Maximally Inverse* thinking, a phrase that I coined: OrganJet takes the patient to the organ, rather than bringing the organ

TABLE 7 *OR and Quantum*

OR framework	Quantum topic
Integer Programming	Quantum (Inspired) Computing
Queueing Theory	Buffering of Flying Qubits
Semi-definite Program	Quantum Information Science
Markov Decision Process	Distillation in Quantum Switches

TABLE 8 *Academic-Capitalist-Philanthropist*

Capitalism	Academic Capitalist	Academic	Academic Philanthropist	Philanthropy
Commonwealth Capital PE		Supply Chain New Business Models		
	SmartOps	Healthcare	OrganJet Nudge Videos	RAGS Foundation
Neotribe VC		Quantum		

to the patient; Nudge Videos influence the NOK after the potential donor is deceased, the last possible point in time when one could be helpful, in contrast to nudging first-time drivers at the Department of Motor Vehicles, likely the earliest time when one could choose to become a donor.

I now teach this way of thinking to award-winning social entrepreneurs, from more than 20 countries, annually since 2017, at the Harvard-WEF Schwab Social Entrepreneurship Leadership Program at Harvard Kennedy School (HKS).

4. The second quantum revolution

I have had a three-decade long avocational fascination with physics. The possibility of fusing this (until now, a purely intellectual) hobby with my professional career was too tempting to ignore.

I created the field of Quantum Integer Programming (QuIP) in 2018 (Bernal *et al.,* 2021). NASA/USRA (Buberniak, 2020) and TED (Tayur, 2021) have been channels to disseminate this work to technical and non-technical audiences, respectively.

Some ways for our OR/OM community to participate in *The Second Quantum Revolution* are listed in Table 7. For the computationally oriented, the one-to-one correspondence between certain combinatorial optimization problems (for example, that underlie cancer genomics (Alghassi *et al.,* 2019b)) represented by a Quadratic Unconstrained Binary Optimization model, which maps directly to the Ising model, creates wonderful opportunities to contribute to *quantum computing* (Alghassi *et al.,* 2019a). For the more mathematically oriented, the connection between Quantum Information Science and Semi-definite Programming is a natural pathway to learn about *quantum sensing* (Siddhu & Tayur, 2022). Those interested in queuing (Siddhu *et al.,* 2021) and Markov Decision Processes (Kumar *et al.,* 2023) can find exciting applications to tackle in *quantum communications*.

Our community has stayed away from being at the forefront of developing new (computing) hardware, focusing on algorithmic analysis and development. I now have an opportunity (on a DARPA grant with BBN-Raytheon and engineering physicists at Cornell University (Onodera *et al.,* 2020)

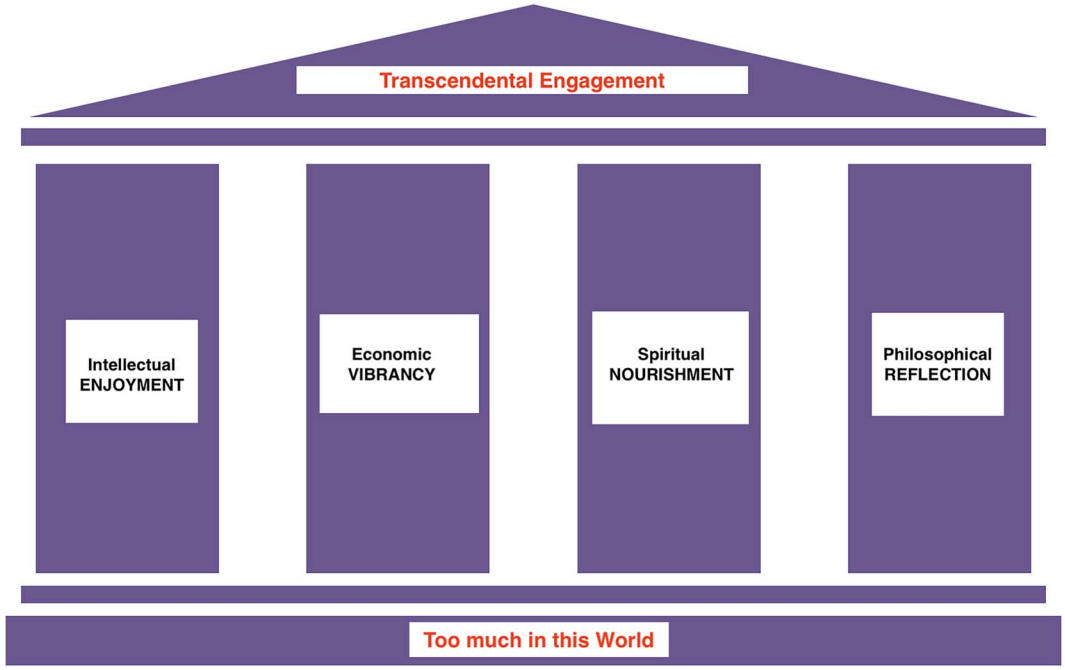

FIG. 4. Transcendental engagement.

to build an entirely new type of non-Turing computing device based on Floquet engineering and superconducting qubits to solve hard combinatorial problems! I invite others in our community to join me in contributing to *The Second Quantum Revolution*.

5. What are we doing here?

What is the meaning of one's professional life (beyond teaching which I have previously discussed (Tayur, 2016))? How can we help bring novelty, such as AI for Medicine (Dai & Tayur, 2022), responsibly into this world? How can we improve fairness in our society (Bernards *et al.,* 2022)? How can we ethically (Kim *et al.,* 2022) improve the lives of many? How can we prevent atrocities (Cho *et al.,* 2019) in global supply chains? How can we advance our civilization through pushing the boundaries of computing hardware (Prabhakar *et al.,* 2023)?

Table 8 shows how I view my professional activities (Tayur, 2017). They centre on academic research (which over three decades has spanned supply chain, new business models, healthcare and quantum); they then branch out, both towards Capitalism and towards Philanthropy, through entrepreneurship (SmartOps, OrganJet) and through judicious use of money (Neotribe Ventures and RAGS Foundation), which was itself earned by *implementing novelty* in a scalable manner with a channel partner (EIO, SmartOps and SAP).

My contemporary response to Emerson (Emerson, 1837) is summarized in Fig. 4: it provides a framework of *Transcendental Engagement* that I have developed for myself, to shape my own professional life that rests on four pillars: intellectual enjoyment (bringing novel concepts into this

world), economic vibrancy (through implementing and facilitating novelty), spiritual nourishment (improving fairness and equity, combating atrocities) and philosophical reflection, that is, *How can we, through our professional craft, leave worthwhile footprints on the sands of time?*

Acknowledgements

There are way too many people who have been my partners and collaborators—from Industry, Academia, Government—in this journey to list by name. Indeed, to just mention briefly, even a couple of sentences each, on how they contributed will take more pages than the main text. Thanks to all.

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