Innovation, Enterprise and Physics Education: Weaving Paradigms for World of Work

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Abstract. There are global concerns about the employability potential of the young graduates. Increasingly, the young are expected to contribute to the innovation ecosystem, be economically productive, and capable of being self-employed, enterprising and entrepreneurial. An overview of the national policies and practices is provided to illustrate the sweeping changes being brought abut at all levels of education. The paper explores how enterprise and entrepreneurial education can be embedded in mainstream physics education. The assertion is that dynamic and creative teaching-learning environments have long included action-learning in various measures. Case study of work undertaken by the author exemplifies how collaborative student projects provide the opportunity for embedding innovation and enterprise in curricular and cocurrricular activities in transdisciplinary contexts. An overarching perspective highlights challenges, opportunities and implementable action plans.

1. Introduction

These are exciting times for the young. Nations across the world are increasingly aspirational. Emerging economies, in particular, see a strong correlation between science, technology and socio-economic progress. On one hand, there is greater investment in human and social capital; modern infrastructure and better quality of life. On the other hand, there is policy commitment to sustainable development goals, management of natural resources, and overcoming challenges posed by unrestrained growth to environment. There is increasing sensitivity on issues of equity and need for affirmative action along with manifold expansion of outreach programmes. The changing national goals, however ridden with contradiction and challenge, are providing many opportunities for participatory action and engagement at both local and global level.

All this needs skilled manpower capable of addressing societal problems, sustainable development needs and global challenges. This has led to transformative changes in the agenda of science education and explicitly articulated concerns about the career preparedness and workplace trajectory of science graduates. Trailblazing examples of young innovators and entrepreneurs leveraging disruptive technologies and new models of economic activity have set new benchmarks and expectations. In India specifically, it is increasingly felt that to leverage demographic advantage and remain competitive, the young should be encouraged to become entrepreneurial. In recent times, government national schemes have motivated setting up of innovation hubs and incubation centres in colleges and universities. To catch them young, schools have been encouraged to set up tinkering labs. Going beyond the engineering streams, colleges of liberal arts and basic sciences, and all universities, are also being nudged to develop entrepreneurial mindset, innovation cells and incubators to participate in the new India growth story. A commensurate National Education Policy spanning all educational levels, from schools to research universities, will be implemented from 2022. The results are visible as the country records a fast growth in the startup ecosystem.

1.1. Science, Technology and Exponential Transformation

The progression from being a knowledge-based society to an innovation-based society is clearly discernible, more so after the onset of the pandemic. The ubiquitous information and communication technologies have ushered new ways of knowing, learning and sharing, disseminating new skills in large populations. The concept of workplace is changing as organizations undergo rapid digital transformation and are increasingly networked. The demographics too is changing as the workforce is increasingly mobile and organizational flux is the new normal. Armed with new technological tools, the young are ready to carve a new identity in a bold world characterized by a completely new paradigm – the 6D's of exponential technological transformation made possible by spectacular access to computing power and mobile technologies. Rapid *Digitalization* of devices has overcome the initial disbelief in their potential, and dismissal as science fiction generated *Deception*. Evolution of these devices and emerging technologies – such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Hyperautomation with a range of tools like Robotics – have caused widespread *Disruption*, subverting established industries and organizations. *Demonetization* and *Dematerialization* of what was once physical has made technology freely accessible and led to *Democratization*, making technologies cheaper and cheaper; and accessible to anyone, anytime, anywhere. Digital transformation, disruptive technologies, and access to high-speed communication make it possible to create new products and set up enterprises in matter of months if not days. These are seen as catalysts to economic growth. Natural inhabitants of this world, both male and female students –the millennials to technology born – are eager to carve a new identity for smart future driven by the fourth industrial revolution, by Change 4.0.

2. Fostering National Innovation Ecosystem

In the last few years, a major national policy thrust has been on creating and promoting a culture of innovation and entrepreneurship across the country, with special focus on the education sector. Launched in 2016, *Atal Innovation Mission* is a flagship programme of the government that aims to create a facilitating environment for transformation of ideas into innovative and impactful solutions at schools, universities, research institutions, micro, small and medium enterprises (MSMEs) [1]. In a multi-pronged approach, it has established five initiatives that have entailed setting up Atal Tinkering Labs (ATL) in schools; Atal Incubation Centres (AIC) in colleges and universities; New India Challenge (ANIC) programmes; Atal Research and Innovation for Small Enterprise (ARISE) centres; and Atal Community Innovation Centres (ACIC). The comprehensive approach involves reaching out to all possible stakeholders; providing platforms for generation of innovative ideas; mentoring and requisite support geared towards talent utilization, self-employment and entrepreneurship. Rigorously implemented, monitored and managed with public-private partnership, the mission has been successful in changing the innovation landscape of the country.

2.1. Innovation Ecosystem in Schools

The Atal Tinkering Labs (ATL) have been established at the school level with the goal of igniting curiosity, promoting hands-on explorations in STEM domains; and providing an introduction to technology innovation at a very young age. The ATL provides within the school access to a workspace well equipped with state-of-art scientific instruments and gadgets, low- and high-tech prototyping tools, do-it-yourself kits leveraging microelectronics, open-source microcontrollers, range of sensors, Arduino, Raspberry, Computers, 3D printers, Robotics, Internet of Things (IoT), and other advanced technologies. The strategic intent is to give young students a lab of their own where they can explore problems of their own choice and learn innovation skills. ATL is the playground for inculcating 21st

century skills. It is helping young students develop design mindset, computational reasoning, programming skills, adaptive thinking and problem-solving skills. Most importantly, students are getting an early exposure to disruptive tools and technologies that are increasingly playing a critical role in building the innovation ecosystems and will be the bedrock of the workplace of future.

The programme takes students through a well-calibrated journey that goes beyond the existing curriculum and traditional pedagogy to create a radically different innovation led microenvironment. Adequate one-time seed grant and annual maintenance grants are provided. Activities are carefully crafted and guided by teachers and mentors who have undergone training, and by experts from outside the school system. ATL course modules have been developed by leading national and multinational technology companies. The endeavour has been to integrate ATL within the curriculum and the timetable as activity periods in addition to making the facility available pre- and post-class hours; and during holidays. The operations are at four levels. Level 1 modules familiarize all students with the new age technologies, ideating projects and tinkering. At level 2, interested students are introduced to design thinking, digital literacy, computational thinking and Do-It-Yourself activities to begin tinkering. At level 3, interested students advance to physical computing and undertake projects and make prototypes. Finally at level 4, the motivated segment is encouraged to innovate and address real-world problems. Thus, the cycle leads students from being tinkerers to makers and innovators.

The programme has worked around several challenges It has generated a rich repository of resources, many best practices and documented case studies. Currently, it is close to achieving its target of 10,000 ATL labs spreading from metropolitan cities to the remote corners of the country, with an unprecedented outreach to around one million students from grades six to twelve. The model conceptualizes these as innovation hubs that will engage neighborhood schools, parents, local communities, experts, volunteering organizations and partnering institutions. The idea has caught the imagination as best practice and been independently adapted by many non-ATL schools.

2.1.1. Challenge-based learning/innovation. ATLs are viewed as incubators for channelizing the talent of young students. Students get several opportunities to showcase their talent by participating in community days, monthly challenges, tinkering and innovation festivals and marathons. The highpoint is participating in national innovation challenge, being nominated for internships, international events and exchange programs. The achievements are recognized and celebrated at the highest levels of the government.

Early emphasis is on ideas and innovations that address the needs of communities, societal problems, development goals and related national missions. As an illustrative example, an Atal Tinkering Marathon posed a six month long nationwide challenge on focal themes of Clean Energy, Water Resources, Waste Management, Healthcare, Smart Mobility and Agri-technologies. Rigorous multistage evaluation selected top 100 teams based on novelty and prototype functionality. They were guided to refine and rework their presentations. Then top thirty teams were selected for mentoring support by industry and start-up incubator to test the innovations in community. This process modeled the typical journey from idea to innovation, prototype to product, mind to market.

2.1.2. Fostering innovation. There are several other initiatives that also aim to catch the students young and orient them towards using S&T for innovation. A few illustrative examples are included herein.

INSPIRE (Innovation in Science Pursuit for Inspired Research) is flagship programme of the Department of Science and Technology that has well established schemes ranging from early school years to supporting studies in science and early research career in institutes of higher education and research. Within this, MANAK (Million Minds Augmenting National Aspirations and Knowledge) has been floated in collaboration with the National Innovation Foundation (NIF), an autonomous body dedicated to promoting grassroot innovations [2]. It targets students of age group 10-15 studying in grades 6 to 10. It tweaks an earlier programme of engaging students in project work to leverage the student talent with help of NIF. The aim is to generate one million innovative ideas with potential to address societal needs. The programme builds awareness and capacity of functionaries across all districts and states of the country through regional workshops. It mandates organising of internal idea competitions in schools who can nominate up to 5 best original ideas or innovations. NIF selects the top 1,00,000. An INSPIRE cash award of significant renumeration is directly transferred to the bank accounts of the short-listed students to enable them to work further. Subsequently, through competitions at various levels, 1,000 ideas/innovations are selected for a National Level Exhibition and Project Competition (NLEPC). At this stage, NIF provides mentoring support to students for development of prototypes, in coordination with reputed academic and technology institutions of the country. Top 60 innovations are shortlisted for national awards based on novelty, social applicability, environment friendliness, user friendliness and comparative advantage over the existing similar technologies. NIF provides further support for product/process development and display at the Annual Festival of Innovation & Entrepreneurship (FINE).

Dr. A.P. J. Abdul Kalam Ignite Awards have been instituted in the memory of former scientist and president of the country. Launched in 2008, these are being administered by NIF. The annual competition invites creative, original technological ideas/innovations from students up to grade XII or age 17 years, in and out of school. Students are encouraged to solve day-to-day problems they observe in their communities by applying traditional knowledge (TK) practices or designing innovative devices/machines. All practical and useful entries are provided mentoring support and in deserving cases, patents are filed in name of the student. Some of these ideas may be licenced and have evolved to become entrepreneurial ventures.

Multidisciplinary in nature, examples of successful innovations exhibit the spirit of young India full of idealism and optimism. Vinisha Umashankar (14 years), winner of IGNITE Award 2019, designed a Mobile Solar Ironing Cart with a roof mounted solar panel that produces 250 watts/hr and takes 5-6 hours to charge a 100Ah battery, to enable use of an electric steam iron for pressing clothes. In absence of sunlight, it can be powered by pre-charged batteries, electricity to diesel-powered generator. It has obvious advantage over the charcoal-filled cast iron-box traditionally used by street corner vendors to iron clothes. At a rough estimate, there are 10 million such boxes that consume 5 kg charcoal per day. The cart can also be fitted with coin operated GSM PCO, USB charging points and mobile recharging facilities to provide additional services and enhance income. Vinisha won the prestigious Swedish Children's Climate Prize in the Clean Air category in 2020. She was also the Earthshot Prize finalist. Invited to the 26th UN Climate Change Conference to speak at the world leaders' summit in November 2021, she made the clarion call " … you need to back our innovations, projects, solutions … you need to invest your time, money and effort in us to shape our future!"

Dr. Abdul Kalam Space Research Payload Cubes Challenge conducted in 2021 involved about 800 students from government schools from grades 6 to 12 from across the country and students of two Engineering colleges. They were assigned the task of designing and launching 100 femto satellites through a high-altitude scientific balloon. Several online lectures and a hands-on workshop was conducted to enable the students. The satellites were designed to provide live data for studies based on agriculture, ultraviolet radiation, natural composite materials, vibration, wind speed, global warming, ozone depletion, among others. The data can be analyzed. With the high-profile launch on 7 February 2021, the event found a place in the Guinness Book of World Records. Such early exposure is expected to motivate the young students to pursue careers in space science.

2.1.3. Moonshot generation. The current batches of students are to the millennium born and have the generational advantage. Many of them already have significant expertise in use of digital devices and emerging technologies; or aim to acquire fluency rapidly. They have a smart vocabulary and are aspirational. They see role models in the young stalwarts leading the top technology firms. They are motivated to challenge the status quo, aim at global grand challenges, ideate radical, and find new solutions. For them, nothing is science fiction. They are ready to leapfrog 10X to disruptive change. The Do-it-yourself generation, they are redefining the concept of literacy and learning.

Sarang Sumesh from Kerala, India, made his first robot at the age of three. At age of eight he was the youngest exhibitor at Silicon Valley Maker Faire. By ten he had several innovations such as a cleaning robot, stick for visually challenged, a robotic hand and a smart seat belt.

Samaira Mehta from California began coding at the age of six with help from her engineer father and designed a board game CoderBunnyz to help other children to code, providing basic examples of AI and Java. By age of 11 she was hailed as a tech-entrepreneur and CEO of two companies.

Tanmay Bakshi from Toronto started coding at five; made his first iOS app at nine; and became the youngest IBM Watson Programmer in the world at age of twelve. The key to his success in programming to solve real-world problems is best summarized in his words " *I never knew people coded as a job. I thought it was just another toy to play with."*

Geetanjali Rao at 15 years appeared on the cover of Time magazine as the top innovator kid of the year 2020. Winner Discovery 3M Young Scientist Challenge 2017, she is a serial entrepreneur with innovative processes for detecting lead content in water using nano tubes, detecting Oipoid addiction and detecting cyberbullying early.

The International Science Engineering Fair, the largest global high school STEM competition with top award of USD 75,000 bears testimony to the potential of the young. It brings together the next generation of STEM talent to present their original research ideas, leveraging the most advances ideas and technologies to address outstanding problems. The 2021 winner Michelle Hua from designed an artificial intelligence-based algorithm for human action recognition with a novel deep learning framework that outperforms all similar state-of-the-art algorithms.

Krithik Ramesh, 16, from Colorado**,** won the top ISEF award in 2019 for developing a machine learning and computer vision technology-based system to help orthopaedic achieve greater accuracy for screw placement during spinal surgery. This is a *Pokeman Go* like augmented reality system. He showed that his method has the potential to decrease operating time by at least 30 minutes, reduce physical therapy recovery time by four weeks and diminish the negative side effects associated with traditional medical imaging. The 2018 top award went to Oliver Nicolls for designing a window washing drone for high rise buildings that can withstand wind speeds of 28 mph.

2.2. Incubation Centres in Colleges and Universities

Educational institutions of higher learning are being encouraged to set up incubators individually or in association with other institutions/ entities. The objective is to promote both, commercial and social entrepreneurship and trigger the growth of start-ups in every sector across the country. Competitive financial support is available under AIM for greenfield incubators or scaling up existing ones. These are utilized for creating lab, technical, prototyping and coworking facilities. Training, professional advice, mentorship and partnerships provide the connection with the larger entrepreneurial ecosystem; and most importantly, access to seed funding and venture capital. So far 68 incubators have been set up. These have given rise to 2200+ start-ups of which 625+ are women led.

While science and engineering institutions are well geared to undertake innovation, liberal education systems – colleges and multidisciplinary universities that constitute the backbone of the educational system – are the new entrants in this space. Increasingly they are leveraging the plethora of government schemes to set up technology-based business incubation facilities, and/or programmes integrating business skills, self-employment and entrepreneurial opportunities with multi-stakeholder support.

2.3. National Innovation and Startup Policy 2019

Fostering this culture of innovation is the well-defined 360-degree support proactively provided as part of nation's strategic vision. National Innovation and Startup Policy 2019 provides the framework for creating a robust innovation, startup and entrepreneurship ecosystem across higher education institutions, actively engaging students and faculty [3]. It brings uniform policies on management of Intellectual Property ownership, technology licensing and institutional startup policy. Under this, Institution's Innovation Council (IIC) can be established on campus through competitive grants. IIC scouts and pre-incubates ideas; and supports students as they work to transform these into prototypes. Periodic workshops, seminars, interactions with entrepreneurs, investors, and professional are organized mentor a pool for student innovators and enhance their cognitive and technological capabilities. IICs network with peer institutions and national entrepreneurship development organizations. Students are mentored to participate in national and international Hackathons, idea competition, mini-challenges organized with the involvement of industries. The competition is intense. Institutions are also assessed on Atal Ranking of Institutions on Innovation Achievements Framework (ARIA). All this is accelerating cutting edge research and innovation and deep-tech entrepreneurship.

2.4. New Education Policy

New Education Policy 2020 [4] to be implemented at school, college and university level from 2022 is the overarching transformational reform; the national innovation missions and startup policy become important supplements and scaffolding. The epicentre of NEP is creativity, research, innovation and entrepreneurship. The strategic intent is to unleash demographic dividend by creating industry ready workforce well-equipped with 21st century skills to meet the global industry requirements and also capable of self-employment. The goal is also to put the country on the leading edge of knowledge creation, scientific research, and technology innovation at par with the global best.

A the school level, the focus is on breaking silos between curricular and co-curricular activities and moving towards competency and outcome based education. The curriculum aims for early development of curiosity, logical thinking, discovery-based learning, and problem-solving, experiential learning, critical thinking, discussion and analysis based interactive teaching-learning; and development of scientific temper. There is a major emphasis on digital literacy, computational thinking, integrating ICT and coding at a very early age.

Higher education has to dove tail these changes. Here again, a holistic approach underpins proposed changes to ensure development of broad-based competencies and outcome-based learning. It has entailed designing new structures for degree programmes offering greater curricular flexibility with multiple exit points; introduction of a multidisciplinary and transdisciplinary culture through formal integration of sciences, social sciences, humanities, art, culture, languages, etc.; integration of vocational education with mainstream academic studies; practical learning; opportunities for apprenticeship and internship with business, industry and other entities; access to state-of-art research facilities enabling research-based specializations on the frontiers. Cutting across all domains and levels of study, there is a strong emphasis on values and ethics; on understanding societal needs, participatory community engagement, solving real-world problems and realizing development goals.

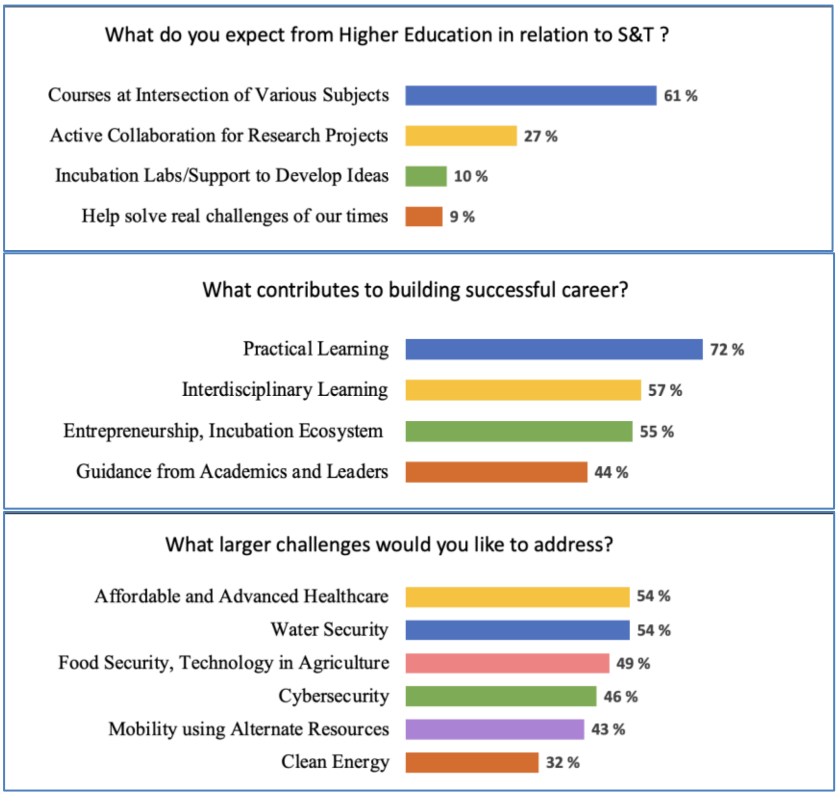
3. Reimagining STEMM Education

Recently, a major survey titled Reimagining STEM Education was conducted by Future Skills [5], an initiative of the National Association of Software and Services Companies (NASSCOM), a not-for-profit Indian consortium created to promote the development and growth of the country's IT industries. It's education initiative provides additional training and skill enhancement to improve graduate employability; and also interface between industry, academia and government. The survey covered 11234 students of grades X, XI, XII in 422 cities, pan-India. The objective of the study was to understand perceptions of students about the senior school education system and their future career aspirations. It aimed to study the gaps compared to international education; challenges faced by students; drivers for choosing an institute for higher education; perspective on exchange programs; students' subject preferences; and perceptions on future technical skills

Figure 1 depicts the responses to three select questions:

(i) What is the expectation from higher education with respect to S&T?
(ii) What contributes to making a successful career?
(iii) What larger challenges would you like to address?

Figure 1: Student Response to Survey Questions on (i) expectations from higher education; (ii) factors contributing to a successful career; and (iii) the real-world challenges they would like to address.



The findings show that students perceive that currently their education is too theoretical with little exposure to industry; it lags in providing practical/application-based learning. The students

(i) favour application-based learning over rote learning and opportunities for out-of-box thinking;
(ii) prefer institutions that will enable practical and blended learning; and interdisciplinary learning leading to jobs/career success.
(iii) aspire for education to solve real-world problems such as in the areas of affordable and advanced health-care, water scarcity, food security and technology in agriculture, cyber security, mobility using alternate resources; clean energy.
(iv) seek technical skills in emerging technologies such as artificial intelligence and machine learning; critical thinking and good communication skills.

Salient recommendations that emerge from the survey of students' expectations is that STEMM education needs

- upgrading of the curriculum to include practical/ application-based learning that is industry relevant;
- introduction of new-age technical skill courses on emerging technologies; and interdisciplinary courses addressing outstanding real world problems;
- development of soft skills such as communication, creative and critical thinking skills; team work, collaboration, internships, and workplace ethics; and
- training and reskilling teachers for new age skills; educational best practices, practical and blended learning; provide them research exposure, and developing professional standards.

The survey results provide a compelling evidence-based support to the direction being adopted by the new education policy with focus on transdisciplinary studies; and creating a strong research and innovation ecosystem.

4. Physics education and world of work

It is well recognized that technology and data are all pervasive and already changing the profile of jobs in the workplace. The pandemic has globally accelerated technology adoption and disruption. AI, cognitive computing, robotics are expected to radically transform or make jobs vulnerable to automation. There is explosion of contingent work or so-called gig economy. Newer technology applications and new markets are impacting the workplace like never before. Additionally, the work culture is also changing the work-life dynamics. There is greater autonomy and flexibility to work anytime, anywhere. Virtual and hybrid modes of working place demands on the workforce to be self-driven, self-regulated, resilient, adaptive and agile. Rising challenges for world economies and shrinking employment avenues are likely to place unprecedented pressure on the education system. These necessitate major reforms that will empower students to be employable in the future workplace and also have potential for generating self-employment.

4.1. Physics students' skills, knowledge and employment profile

It is difficult to find data in India on fields in which physics students at various levels find employment. American Institute of Physics (AIP) statistics [6] provides this data which can be used to glean insight that is may be largely valid in context of other countries as well. The global trend is that a majority of physics bachelors who enter the workforce are employed outside of academia. Figure 2 depicts the trends for this cohort and suggests that about half enter the workforce. Of these, 2/3rd are employed in private sector with jobs in engineering, computer or information systems and other STEM disciplines. A far smaller number have physics/astronomy related jobs. Interestingly, 13% of employed in non-STEM areas use their knowledge to solve technical problems; however, 7% rarely or never do so. Along the academic pipeline, only 1/3rd of those with Ph.D. in physics join academia.

Figure 2: Statistics on where the Physics Bachelors are employee one year after graduating. Batch of 2017-2018. Source: AIP Statistics.

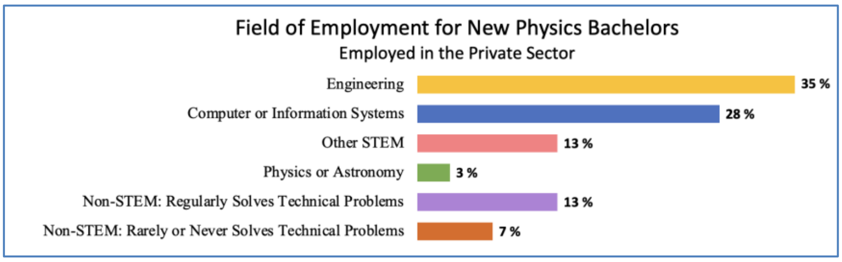
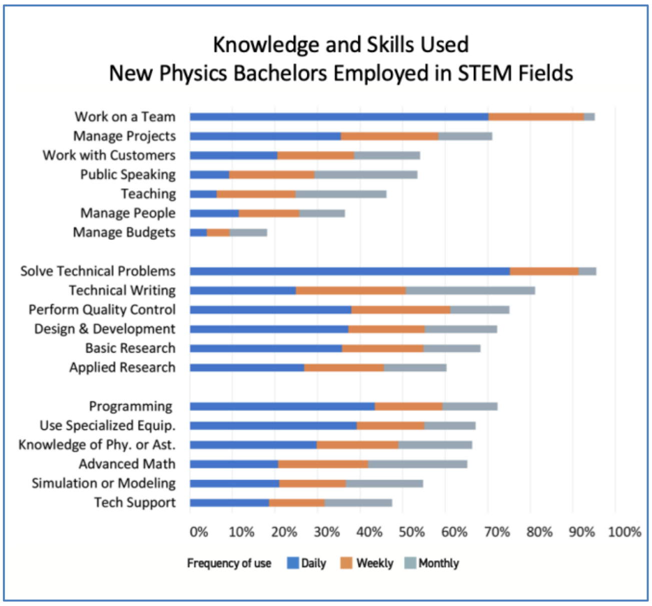


Figure 3 depicts the knowledge and skills use by new PhDs who enter the workplace. Technical skills are predominant in day-to-day functioning (50-75% of work time) while basic and advanced research skills, capacity to operate specialize equipment, apply basic and advanced principles of physics is evoked much less (15-25%). Survey data also shows the workplace requires team work and project management skills at a far higher rate than other skills such as technical writing, budgeting and working with clients.

There is evident concern on how productive are those who drop out of the education system; and where in the world of work is the highly trained human resource. The leak along the academic pipeline raises a fundamental question: Should physics education focus merely on domain knowledge or should it also address concerns on employment and make students ready for diverse careers with technical expertise, early exposure to new age technologies in tune with the contemporary and forecasted needs of the workplace.

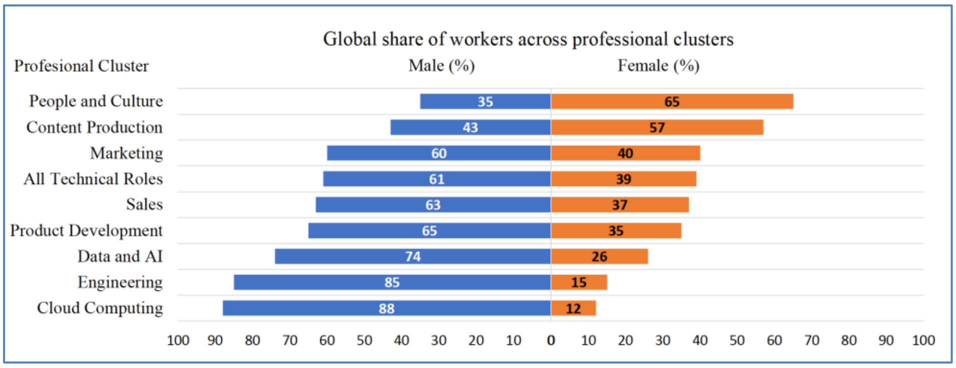
Figure 3: Knowledge and Skills used by New Physics Bachelors employed in STEM fields



4.2. Gender gap in skills for the future

An important factor to consider herein is the gender gap in skills required and share of females in the workplace. According to the World Economic Forum Report 2020 [7], females have significantly lower skills in disruptive technology (29%) and lag behind in other requisite skills in business, all other technology clusters, specialized industry needs and even soft skills (~ 40%). Closing the gap requires that females acquire these skills at the educational level, be provided training, reskilling and upskilling. Figure 4 depicts the share of the professional workspace on the frontiers of the new economy. Females now are the predominant contributors to jobs relating to people, culture and content production. There is parity in all technical roles taken as a cluster. However, given the lower enrolment in engineering, computer science and high-tech courses, females global share of jobs in the disruptive space is rather low ranging from 35% in product development, 26% in Data and AI to mere 12% in cloud computing. The trend is similar for India.

Figure 4: Share by professional cluster. World Economic Report 2020.



There is recognized need for advancing gender equity and providing a level playing field in the workplace. Thus, special attention is needed on increasing female enrolment and skill development in disciplines that will provide skills necessary for the jobs in the workplace.

5. Embedding enterprise and entrepreneurial education

Enterprise and entrepreneurial education has never been more crucial. The previous sections elaborate the policy frameworks established in the last few years for creating the requisite innovation ecosystem in mission mode. The NEP envisages sweeping reforms. These can be anchored in the positive experience of implementing various schemes under the innovation mission and their impact on startup landscape of the country. However, affecting transformative change on a large scale is a dauting task given the size of the population, scale of the education system, inherent diversity in socio-cultural-economic contexts, prevalent lack of uniform access to fiscal, infrastructural and educational resources, quality of teachers, diversity in systems of curricular praxis, assessments and examinations, and much more.

Science education is already riddled with many challenges. Most students find physics in particular difficult and abstract. Typical classroom focus is on fundamental principles replete with exercises that disseminate idealization and simplification of physical systems. Not enough consideration is given to how these principles can be applied to solve real-world problems. Data shows flight of talent from physics to other science/ non-science disciplines and non-STEM professions. Then the moot question is how best to embed enterprise and entrepreneurial education in the mainstream science education and make this accessible to all or significantly large populations of students.

The plausible answer lies in recognizing that successful scientists and entrepreneurs share many traits, attitudes and skills. Effective teaching-learning by its very nature requires students to be enterprising. Research-based technology-enhanced active-learning pedagogies and project-based learning environments provide the necessary framework and plethora of opportunities for developing 21st century skills. It is easy to discern the overlap with elements of enterprise and entrepreneurial learning; and determine what more needs to be done to align the goals.

Enterprise entails generation and application of creative and novel ideas; and understanding how these can be developed into innovative products and services. Entrepreneurship education entails application of enterprise skills and competencies to capitalize on ideas for creation of cultural, intellectual, social and economic value. This may lead (but not necessarily so) to creation of an organization or a venture with or without commercial objectives.

Moving from enterprise to entrepreneurial venture needs many bridges. It requires developing resilience, capacity for opportunity and risk assessment, and risk tolerance. Both for-profit and not-for profit ventures need project management, administrative and accounting skills; fiscal acumen, commercial awareness and sense of business; networks, linkages and community connect. While these underpinning skills are important in contemporary contexts, not every student/faculty/staff or institution would want to become an entrepreneur, create ventures or startups. However, the capacity to transform creative ideas into actions is an important life skill and a profession skill – imparting these has always been the higher goal of learning. Whether students choose to be enterprising or entrepreneurial, weaving enterprise education through experiential learning for all students provides wider contexts for learning; for cultivating the mindset, attitudes, behaviours and competencies for crafting a successful life in the innovation society in the making. It prepares them for the future of work.

6. Physics education as an enterprise: a case study

This section delineates specific examples of personal work with undergraduate physics students at Miranda House, premiere institution for women at University of Delhi, and with other organizations. This can be viewed as an institutional capstone project in physics education spanning several decades [8]. It can also be viewed as a social enterprise to address problems in the educational system through action research.

The work has entailed (i) creating opportunities for introducing physics research-based pedagogies in a largely traditional system; and (ii) embedding innovation and enterprise in curricular, co-curricular in transdisciplinary contexts for action-learning; (iii) developing curricular resources, products leveraging appropriate technologies, developing innovative pedagogies, disseminating and assimilating these in mainstream education for transformative change; and (iv) creating student-faculty teams and communities of practice to address socially relevant real-world problems.

The evolution of these programmes provides insight into how pioneering projects provide opportunities to faculty for life-long learning, skilling, re-skilling and keeping pace with disruptive technologies and practices. Engaged faculty is a pre-requisite for development of innovation driven research and enterprise ecosystem.

6.1. Student-based projects as instruments of innovation

The pedagogic merits of engaging students in project work are well documented. What is less well recognized is that student projects provide a tremendous opportunity to subvert ineffectual traditional practices and develop alternatives. Project-based learning provides a framework for innovation. Our own journey began in 1984 when we launched a novel programme aptly called *Learning through Investigative Projects* [9]. External funding helped us to create a project laboratory that could operate as a flexible and cooperative learning environment, that students could call *A Lab of my Own*. A pioneering initiative, it provided a Tinkering Lab or Makers Lab at the undergraduate level. The programme led to establishment of the *D S Kothari Centre for Research and Innovation in Science Education* (DSKC) at the college; it draws the best students from across many more institutions.

6.1.1. Development of effective teaching-learning strategies and skill set. Projects provided us the framework for initiating the student to the craft of the scientist, the innovator, the entrepreneur. Students are in general curious, enjoy working with their hands and the act of building things. The challenge is to temper the flurry of activity usually witnessed in student project work with the rigour of scientific method, systematic thinking; to construct a learning environment that is both hands-on and minds-on. The model adopted is of cognitive apprenticeship. In many of the problems, we were ourselves first time learners. Then witnessing the cognitive processes underlying learning played a significant role in transformation of student from being a passive recipient to someone actively engaged in the process of construction of her own knowledge. By carefully balancing teacher guidance and self-paced enquiry, we tried to ensure that open-ended projects, in addition to enhancing the procedural and conceptual skills of the students also yield outputs utilizable by the formal system.

The programme has engaged very large number of students at any time. Then learning pathway have involved identification of student interest, formation of collaborative groups, and extensive brainstorming on project ideas. Each problem is parsed into small component exercises carefully designed to introduce key concepts or tools required to bring students to the threshold from where actual investigations could begin. A conscious effort is made to find low-cost solutions using techniques and facilities easily acquired by an average student laboratory; undertaking several stages of design and re-design; appropriate use of technology and sophistication. Considerable emphasis is placed on validation of results, the art of gradual refinement of measurement techniques and theoretical models; and most importantly, building capacity and resilience to handle negative results.

Projects allow students to learn in multiple contexts accessing multiple resources. Transdisciplinary problems also necessitate discussions with technicians, faculty from other disciplines. Interacting with experts, each having specific skills and characteristic method of work gives students a wider perspective of the problem as well as multiple benchmarks against which to evaluate their work.

6.1.2. Development of curricular resource materials. Although the scope of investigations is unlimited, we often looked for ideas from within the existing curriculum, or such frontier areas that ought to be included in the formal curriculum, mostly targeting the laboratory programmes. An important objective has been to craft setups for demonstration of physical phenomena, or replace outdated measurement techniques leveraging microelectronics and computer-based technologies. Activities in our project laboratory have been based on two simple propositions. One, there is work to be done. Two, the work has to be of value to others. The first has provided the student as well as the teacher a context for learning. The second has ensured quality in effort and the end product. It has also made learning profitable.

Working on projects in programmes with larger aims, students have to learn to work cooperatively at two levels: one, within their own team and two, with groups working on other projects. Through vibrant discussions, they arrive at shared understanding of the problem and its solution. Inasmuch as the projects invoke skills in multiple forms, expertise is usually distributed across a large number of students. The knowledge that apparently disparate projects will be linked together to create a single curriculum package or comprehensive resource ensures cohesiveness in the entire cohort.

6.1.3. Prototype development. In a dual pronged approach, while open-ended investigations are encouraged, all students also have to undertake well-defined tasks that lead to product development and tangible gains. An important requirement of all projects that entail use of electronics in instrumentation are required to package their working circuits and contribute these to the project laboratory for use by others. Fabrication of any equipment also has to be accompanied by high quality blueprints for replication. Considerable effort is expended in perfecting prototyping skills, testing, debugging, calibrating. Students learn to optimize aspects such as overall cost, technical features, ease of use, aesthetic appeal, robustness, etc. The final design conforms to the blueprint accepted by the entire cohort so that the work produced by different groups can ultimately be branded together.

Development of software follows a similar approach. In the early years, students were encouraged to write rudimentary programmes for their individual needs such as for data acquisition, data modelling, manipulation or analysis. Then these were assembled into powerful menu-driven utility programmes for use by subsequent groups of students. Now powerful open-source tools are available. Students are now the more adept partners. We depend critically on student programmers for creating powerful software packages and applications.

6.1.4. Illustrative examples of innovative educational products and resources. Specific products that have been developed show how our expertise evolved and kept pace with rapid changes in the technology, often staying far ahead on the curve than other academic institutions.

(i) Laboratory Instrumentation. A large number of setups for specific experiments; classroom demonstrations; test and measurement instruments; workboards for teaching of functional aspects of analogue, digital, microelectronics and embedded systems were developed. Some of these were adopted in the advanced laboratories at postgraduate level.

(ii) Science Online Microcomputer-Based Laboratory (MBL). A comprehensive low-cost MBL [10] was developed indigenously by stringing together a very large number of innovative student projects. The hardware included interface cards for data-acquisition and control; transducer and sensor circuits for measurement of various physical quantities; specially designed work-boards for learning principles of interfacing; and dedicated setups for a range of physics, chemistry and biology experiments. The package also included menu driven software, detailed application notes and experiment manuals. The emphasis was on how computer-based tools can augment the learning of basic concepts and provide a rich learning environment for comprehensive understanding of various techniques employed in exploration of a process.

(iii) Mobile! MyLab, Anytime, Anywhere. The project aimed to explore the potential of the ubiquitous smart phone using the onboard sensors as a versatile instrument to carry out a comprehensive set of basic science experiments, spanning physics, chemistry and biology in multidisciplinary contexts, develop a product including hardware, software and appropriate courseware. Significant progress was made. Several experiments were presented at student research conferences.

(iv) Eureka! MyLab, Anytime, Anywhere. Many schools, especially those run by city municipalities and in smaller towns and areas, do not have well equipped labs. A multidisciplinary team of ten students and four faculty members from departments of physics, chemistry and biology, undertook to design and develop a Lab-in-a-box to enable school students to experience the joy of science, its practical uses and applications. Innovative active learning material in form of flash cards was included in each kit. The material was tested in a series of outreach workshops at schools and later at science fairs by the development team with much enthusiasm; they shared that mentoring school children was amongst the high points of their own education.

(v) Physware Kits. The expertise in indigenously developing educational resources integrating (a) low-cost low-tech locally available materials; (b) appropriate technologies at the optimum level of sophistication for the learning goals; and (c) indigenously developed instruments, equipment and packages such as comprehensive MBL has been instrumental in organizing the flagship Educate the Educator workshop of ICPE and other capacity building programmes [10].

6.2. *Advancing Technology and Research Experience.* The changes in the technology landscape have brought commensurate changes in the curriculum. Yet the lead-lag phenomena exists and it is important to give students hands-on training and experience of technologies yet to be introduced in the curriculum. Students are now routinely using embedded systems, microcontrollers, Arduino and raspberry platforms. Most disruptive technologies including Robotics and 3-D printers are however not yet introduced in the formal curriculum. We established both these labs to provide students early experience of these technologies, easily available in ATLs but usually missing at the undergraduate level. Students learnt to use these through specially designed workshops. The resulting projects included 3-D printing of drones and robotic devices. Students were thus empowered to participate in Innovation Challenges and Hackathons.

Giving students a flavour of rigorous research in all that they undertake is critical for their progression. Thus, in addition to project-based learning, it is important to create opportunities for undergraduate research using state-of-art facilities leading to dissertation work.

7. The Enterprise Skill Matrix

New age education is placing several demands on the skills students must develop to address real-world problems. Training next generation of innovators and entrepreneurs necessitates going beyond the traditional. Three important facets of productive learning are

- Design thinking. Students need to engage with the real-world to understand and determine what problems they would like to address. These have to be well defined before they can be solved. They need to ideate and explore possible solutions, prototype, test and implement. The process may require several iterations.
- T-shaped approach to knowledge and skills. Both, cross-disciplinary expertise and deep discipline expertise are crucial for innovations. Most real-world problems need transdisciplinary approach to solution.
- Lateral thinking. Creative problem solving requires out-of-box thinking; seeing problems in radically different ways allows innovative solutions. It is important to be able to connect the dots to create new patterns or a larger picture.

Going beyond project-based learning, the canvas for institutional mentoring is huge and spans the full range of curricular and cocurricular activities. Departments, labs, societies, clubs, seminars, conferences, workshops, internships, alumni and other networks, volunteering, community work: all provide rich academic, social and cultural experience. Each provides an opportunity for skill development. A possible categorization along four dimensions is:

- S&T skills: Ideation, innovation, research, data collection, analysis, interpretation, problem solving, engineering, instrumentation, fabrication, computational thinking, coding, prototype and product development
- Soft skills: Communication, presentation, technical writing, collaborating, networking, team building, leadership, art of evidence-based argumentation, discussions, debates, conflict resolution

- Project management skills: Proposal, grant and report writing, budgeting, accounting, financial acumen, business sense, procurement, recruitment, HR management, training, publicity pitch, sales, marketing, risk intelligence, event management
- Metacognitive skills: Understanding personal strengths, weaknesses, achievements, aptitude, attitude, behaviour, risk abilities, ethics, leadership, interests, passions

These life skills and professional skills underpin action learning and what are needed under enterprise and entrepreneurial education within the mainstream academia. These can be further augmented be integrating specialized course modules.

8. Agile classroom, Agile Enterprise

The model classroom in the new paradigm can take the cue from what an Agile enterprise is. It has to be capable of making rapid changes and iterative refinements; be adaptable; quality driven; cooperative and collaborative; capable of working in small teams that quickly come together to address problems in short time frames. It has to build small, aggregate and integrate to create comprehensive solutions. Above all, it has to be reflective and have a growth mindset. This is a process, a philosophy and a culture which has been the touchstone of our own work.

9. Challenges and opportunities

The need for integrating enterprise skills, particularly so in STEM education, poses several challenges. Unless the institution has a strong innovation ecosystem crosscutting all facets, it will not be possible to scaleup creativity and train each student to have an enterprising mindset. Then incubation and startup centres will remain exclusive and cater to the very few. Institutions need to build on their inherent strengths and prepare a critical mass of faculty who can comingle the roles of teacher, action researcher and curriculum developer. There are no shortcuts in this process. Active-learning requires faculty-student teams to undertake capstone projects together. Problemsolving leads the team from ideation to prototype, product or process development in outcome-based learning. It leads to skills for lifelong autonomous learning that are immensely rewarding. However, most faculty lay emphasis only on scientific skills. It is important to use the vocabulary that covers the entire gamut of skills developed. Thus, for each curricular or cocurricular activity, students can be trained to consciously include and reflect on the skills they learnt. The metacognitive process is critical for discerning their competencies, skills, interests and aspirations; and most importantly for transferring these to other contexts. It is hoped that interweaving opportunities for development of baseline competencies and skills necessary for the workplace, be it for STEM or Non-STEM jobs, or entrepreneurial ventures.

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