The making of an indigenous scanning tunneling microscope

Pankaj Sekhsaria

This article is an historical account of the indigenous development of one of the earliest scanning tunneling microscopes in India. It was fabricated in the Department of Physics at the University of Pune just a few years after it was first made in Europe. A series of scanning probe microscopes (SPMs) were made here subsequently – a process in which students played a major role. Over a period of two decades these SPMs were used to produce a series of scientific papers besides training students in making, using and modifying the instruments and then pushing them to their limits. Importantly, junk markets, scrap materials, small time spring makers and second-hand dealers and traditional knowledge practices were all an integral part of this enterprise of 'instrument-making' and doing scientific research.

Keywords: History, innovation, scanning tunneling microscope, technological jugaad.

The 1986 Nobel Prize in Physics

ONE half of the 1986 Nobel Prize in Physics[1] was awarded to Gerd Binnig and Heinrich Rohrer of the IBM Research Laboratory, Zurich, Switzerland for the successful development of the scanning tunneling microscope (STM) (see note 1). The significance of the instrument, that is universally credited with having spawned the now hugely popular and ever-expanding field of nanoscience and technology (NS&T) is now well known.

The first significant images from this first STM had been reported in late 1981, but it took a few years more before the instrument gained recognition and popularity[2]. One of the first significant scientific gatherings around the STM was held, in fact, only a couple of months before the Nobel Prize itself was announced. This was the first STM conference organized in Santiago de Compostela, Spain by Nicolas Garcia of Universidad Autonoma de Madrid. It was attended by most of those individuals who find a prominent mention in any historical account of the development of STMs and in the field of scanning probe microscopy (SPM) that followed from it – Binning and Rohrer, of course, but also others like Richard Colton of the Naval Research Laboratory (NRL) Washington, USA and Paul Hansma from the University of California, Santa Barbara, USA[3].

An Indian STM

There is one name in the list of participants of this conference that is of particular interest from an Indian point of view – surface scientist from the University of Pune (UoP), C. V. Dharmadhikari. He attended not only the 1986 conference, but also the second STM conference that was held in Oxnard, California, USA in 1987. About a year later, in 1988, Dharmadhikari successfully installed his first indigenously made STM under the staircase in the Department of Physics, UoP.

Students had also already started working with him on the STM project. In 1987, the first M Sc project[4] related to the STM had been completed under his guidance. The first peer-reviewed article on an aspect of STM construction[5] was published in 1988; the first M Phil degree[6] for the 'development of a simple electronic control system' for an STM was awarded in 1990, and the first doctorate (Ph D)[7] was awarded for STM-related work under his supervision in 1999. In fact, in 1988, when a joint Indo-US project on STM was initiated with S. S. Wadhwa (Central Scientific Instruments Organization (CSIO), Chandigarh, India) and Richard Colton (Naval Research Laboratory, Washington), as the principal investigators, Dharmadhikari was drafted in as one of three other Indian players who had experience and could make a significant contribution.

From 1988 to 2010, the year that Dharmadhikari retired from UoP (see note 2), the Centre for Advanced Studies in Materials Science and Solid State Physics that he headed, had made a series of STMs and Atomic Force Microscopes (AFMs). Twelve students had completed their M Phil degrees[8–12] and eight their doctorates[13–15], all of these while working on various aspects of making these instruments. Many of these students then worked on postdoc fellowships and eventually moved to permanent positions in leading scientific institutions in India and abroad. The research group also published more than 60 papers, including in peer-reviewed journals[16–21].

Pankaj Sekhsaria is in the Department of Technology and Society Studies, Faculty of Arts and Social Sciences, Maastricht University, Grote Gracht 80-82, 6211 SZ Maastricht, The Netherlands.
e-mail: psekhsaria@gmail.com

Many people I spoke to, including Dharmadhikari himself, noted that there was a culture of making instruments in the Department of Physics, UoP from the very beginning. This was itself rooted in the larger shortage of resources available for scientific research in the country[22,23] and an overarching national policy where scientists and technologists were constantly exhorted to achieve self-sufficiency[24,25]. It is in this larger context that the present article explores the scientific journey made by Dharmadhikari and his students; the instruments they fabricated; the materials, processes and people that were recruited in the process; the bridges that were built, new meanings that were generated and the scientific output that they jointly delivered.

Junk markets, scrap materials, roadside spring-making workshops, traditional knowledge practices and the notion of jugaad are not generally associated with the modern laboratory and certainly not with cutting-edge scientific instrumentation and research. Yet, this is exactly what happened here.

Science and technology studies

This article is an outcome of my on-going doctoral research in science and technology studies (STS) as part of which I am trying to understand the 'cultures of innovation' in NS&T research in India. I approach the subject as a sociologist of science and technology (S&T) working in collaboration with the Indian NS&T scientists and researchers themselves.

The research is qualitative in nature and uses methods such as open-ended interviews, historical analysis and laboratory ethnography that are drawn primarily from sociology and anthropology. It is about a 'culture of innovation' that links the macro with the micro and what is done within the lab with the world outside, a world that is a much bigger influence than is generally believed. This is the culture of 'technological jugaad' – innovation that is deeply embedded in the historical, political, social and economic context in which research and innovation happen.

It would be relevant here to note that almost no conversation on innovation in India, particularly north of the Vindhya Mountain Range, can happen without a reference to jugaad. It is a term that is both extremely maligned and used with extreme pride and in what follows there is, first, a brief journey through this world of jugaad. We then return to the laboratory, to the making of STMs and further on to the conceptualization of technological jugaad. The article ends with characterization of this new idea as well as a conceptual framework that should help provide a new understanding of and engagement with innovation as it is nested within the wider socio-cultural setting.

Exploring jugaad

Jugaad is a word in many Indian languages in the upper half of the country such as Hindi, Marathi, Gujarati, Punjabi, Oriya and Mythili, that does not have an easy equivalent in English. The plasticity of the word and the range of its usage are evident in the fact that jugaad can be concept, process and product all rolled into one at the same time; it means reconfiguring materialities to overcome obstacles and find solutions; it could mean working the system to one's advantage, and it is also used as a synonym in certain contexts for gambling and corruption. Jugaad is not just an inextricable part of local vocabularies in India, it is an integral part of the way life is lived and the world negotiated. It is noun as much as it is a verb; an idea and an articulation that has a wide range of meanings and usages that revolve primarily around problem solving or solution finding.

It is not surprising, then, that jugaad comes up repeatedly in discussions related to innovation with as many translations and interpretations as there are authors – 'creative improvization'[26], 'developing alternatives, improvizations and make dos'[27], and 'an arrangement or a work-around, which has to be used because of lack of resources'[28]. A comprehensive and evocative rendering of what jugaad means in its multiple facets is provided by Pavan Varma (see note 3):

> 'There is an Indian expression and, like others, is quite impossible to adequately translate: jugaad. People are encouraged to use some jugaad when faced with a blank wall, or a difficult situation. Jugaad is creative improvisation, a tool to somehow find a solution, ingenuity, a refusal to accept defeat, initiative, quick thinking, cunning, resolve and all of the above'[29].

The diversity and richness are evident in the different ways jugaad is translated, interpreted and used.

Two extremes of looking at jugaad

One strain of discussion on jugaad[30–32], particularly in the popular media, has an evidently feel-good and celebratory air about it. *India Today*, for instance, notes in the editorial of a special issue on innovation that, 'The best translation of that word is a combination of innovation and enterprise (…) *Jugaad* to Indians was both instinct and inspiration. The drive for a better way out, after all, is in India's bloodstream'[30]. This celebratory slant notwithstanding, it is evident that jugaad in such publications is dealt with only in a perfunctory manner. The *India Today* special issue, for instance, profiles 20 innovators and innovations that range across diverse fields such as traditional pottery, modern medicine in the time of the swine-flu epidemic and the development of a pedal power-driven machine for washing clothes. Jugaad, however, does not appear anywhere in any of the detailed accounts of these innovations.

On the other end of this spectrum, jugaad encounters much skepticism and even serious denial[26,27,31,33]. An extreme illustration of this is the recent, wide-ranging and damning account by Birtchnell[34] where he notes that 'jugaad impacts on society in negative and undesirable ways (…) It is wholly unsuitable both as a development tool and as a business asset' (ibid, p. 357).

Krishnan[26] notes on similar lines that 'India remains stuck in a more unscientific paradigm of innovation, often labeled as jugaad' (ibid, p. 170) and that the journey that needs to be made is clearly one away from jugaad and towards 'systematic innovation'.

Prahalad and Mashelkar[27] too dismiss jugaad because 'the term (…) has the connotation of compromising on quality'. They prefer to use the term 'Gandhian innovation' for examples such as the development of the 'Nano', the world's cheapest car available at a price of US$ 2000 or the development of a super computer by an Indian firm at a cost of US$ 20 million.

The position these authors have on jugaad is evident and yet there are two elements that, though unstated, stand out in almost all these narratives. First, there is little, if any, empirical engagement with the concept – we have no details of the examples of jugaad that the authors have chosen to dismiss with emphasis. Second, and this is of particular relevance here, there is no discussion at all of jugaad in relation to research and development in the S&T enterprise of the country.

If jugaad is indeed inferior, unsystematic and a compromise on quality as noted above, it is not a surprise that it has no place in discussion about formal S&T in the mainstream; S&T research is, after all, the holy grail of innovation, creativity and progress. It is a significant paradox then, that the genesis of this article lies in my empirical work that provides evidence to the contrary – jugaad, as I found out and the subsequent narrative will illustrate, appears to be alive and kicking in the modern scientific laboratory, the scientific method and where there is no compromise on the quality of the output either. Importantly, and in line with a fundamental tenet of STS research, I am not using jugaad here to describe and characterize what I, as a researcher, saw in the laboratory; it was a term and an idea that Dharmadhikari, the principal scientist I was interacting with, used himself.

The best-known examples of jugaad

Perhaps, the best known product identified with jugaad is an automobile found across northern and western India that is created using a non-standardized manufacturing process, is not registered with the relevant authorities and therefore does not exist within any formal legal frame. Every such vehicle differs from the other and the only thing that binds them together is the fact that they are fabricated locally and by assembling different parts, commonly from other scrapped vehicles – engines, tyres, wooden planks, steering wheels, seats and even water pumps. They are even called differently in different parts of the country – Jugaad[35] and Maruta[36] in parts of northern India and Chakda in certain regions of western India[29]. The automobile so created is, generally, a locally crafted solution to an immediate problem such as a bottleneck in transporting agricultural produce to the nearest *mandi* (wholesale market for farm produce) or to transport people in a landscape of limited connectivity and mobility choices.

Another well-documented, though less prevalent form of jugaad is the use of an existing artifact for purposes completely different from what it was originally created for – 'materials put to uses few could have imagined'[37]. The best known example of this is again found in parts of North India, where washing machines are used to prepare *lassi*, the popular local drink made from churning curd, sugar and water at high speeds.

Evidently this jugaad is a locally crafted solution to an immediate problem and often a personalized survival tactic in situations of obvious resource constraints and/or denial[28,29]. The jugaad that we are talking about here also involves a prominent element of reconfigured materiality. This, in particular, is what I am calling 'technological jugaad' – a conceptual category that deals centrally with technical and technological artifacts and where reconfiguring materiality to bestow new meaning and create new uses is one of its most important characteristics.

Technological jugaad and STM

It is this concept of technological jugaad that I saw operating prominently in Dharmadhikari's laboratory and his STM enterprise of more than two decades as is illustrated in the set of three quotes that follow:

> 'Like some of the piezos we used from (…) the older models of ink jet printers. Jugaad is something like the spectrometer we used for the tunneling and photon microscopy – we got it from junk, repaired it, improvised and used it. (…) I used to go to juna bazaar [junk market] and find out how much is the resolution of stepper motors (…) To develop techniques to measure how many steps it goes, (…) I think, is jugaad because you find one technique, you use another one, (…) plug them together and once you do it, you have all the technology that they already invented – for something else' (Dharmadhikari, interview in March 2011).
>
> 'There was a huge magnet and I got a bobbin – a plastic bobbin from a tailor and we had a coil on that. That coil was put in a magnet and we hammered it with a wooden hammer. Then we looked at the resonance frequency – simple technique (…). Now with (…) the latest vibration system we are getting the same resonance frequency after 20 years (…) Then we developed one [STM] in a fridge. I had a student from the Middle

East and when he was leaving (…) he gave it to me. So we removed the compressor and it was a good acoustic shell (…) It's a totally new concept – it was used for nanotechnology' (Dharmadhikari (see note 4), Presentation, March 2011).

'To protect the STM from acoustic noise, the total system is encased in a fridge-case (from which compressor was removed), since the fridge case has [a] metal frame which shields the STM from high frequency noise [see Figure 1]. [The] body has glass wool insulation which protects the STM from acoustic noise. It was found that the acoustic signal inside the fridge is less than 2 dB'[15].

Discarded refrigerators[15], stepper motors from junked computers, tubes from car tyres[38,39] [see Figure 2], bungee chords[39] [see Figure 3, which is part of STM in Figure 1], viton rubber tubing[14], weights from the grocers' shop, alluminium vessels generally used in the kitchen and bobbins from sewing machines were only some of the components that went into the making of the first prototype and the other probe microscopes that followed.

The parallel with the examples of jugaad from outside the laboratory is immediately evident – existing materials and artifacts used in completely new ways and/or combined with each other to construct and operationalize a new idea or concept.

Another important dimension to this instrument-building was the collaboration that was struck with a number of other 'unexpected' players. This included, among others, a small-time entrepreneur with a spark erosion machine, a roadside workshop for alluminium sand die casting and the procurement of springs from a workshop owner who could not understand spring constant, but could deliver the needful based on the Dharmadhikari's explanation of the requirements and tacit knowledge embedded in his fingers. In another marginal case, Dharmadhikari even enrolled the traditional plating technique of 'kalai', the practitioners of which travel from house to house in rural and urban areas offering tin-plating services to housewives for their copper and brass utensils.

Figure 1. Scanning tunneling microscope installed inside the shell of a refrigerator after the compressor was removed (photo: Pankaj Sekhsaria).

Instrument-making as a pedagogic tool

It is, however, not just that the instruments worked well and the process of their making was interesting. This process, as Dharmadhikari explicitly noted, also has significant pedagogic value:

'At the same time I realized that doing your (…) own experimentation is always interesting (…) [There is] less throughput, of course (…) but in universities this is a better approach because you are training the students (…) I realized that if I can make simple ones [instruments] through the students, not only [will] we learn a lot about these techniques, (…) but we were also creating future generations which [was] proven later because most of the students got jobs in [the field of] nanoscience' (Dharmadhikari, interview in March 2011).

This is significant in light of one of the key challenges being faced by Indian laboratories today. Balaram[40] notes in his recent editorial that there is the absence of 'trained technicians with a high level of competence in operating and maintaining facilities' and that as a consequence 'Major facilities are sub-optimally used and sophisticated instruments are rarely exploited to their full potential'.

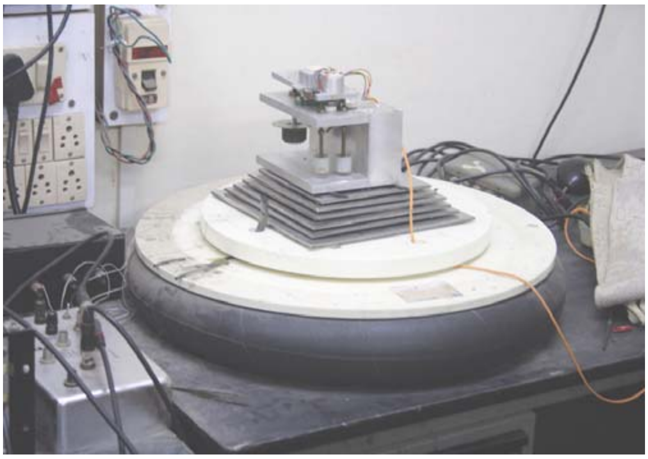

Figure 2. A table-top STM placed on the inflated tube of a car tyre that acts as a vibration isolating device (photo: Pankaj Sekhsaria).

Figure 3. Use of a bungee chord for enhanced vibration isolation (photo: Pankaj Sekhsaria).

These are sentiments that are echoed perfectly in the experiences and opinions of almost all of Dharmadhikari's students. Shivprasad Patil, who is now at the Institute of Scientific Education and Research, Pune, continues to work on the development of AFMs. Patil is explicit in his acknowledgement of the training he received during his doctoral research:

> 'There are various reasons why you should build your own thing (…). If, right from your PhD you are building your equipment there is (…) this freedom and it liberates you (…). The moment you buy one or two crores worth of equipment you are stuck with it (…) Often you are scared to use it to its fullest capacity. (…) [What are] artifacts, what is true information, what is the false signal – those things – you know much better if you build your own stuff. People say you are reinventing wheel [but] it is not so' (Patil, interview in March 2011).

Importantly, this STM example is only one concrete illustration of technological jugaad inside a physics laboratory and there is reason to believe that this is not an isolated case. That we do not know of more such examples in India is not because they do not exist, but more likely, because little effort has been made to go looking for them in the right places on one hand and the refusal to acknowledge or accept them where they might exist, on the other.

Technological jugaad as user-driven innovation

The examples of technological jugaad, whether inside or outside the laboratory, also have a prominent overlap with the now well-established idea of 'user-driven' innovation[41,42]. In a study of the development in the West of scientific instruments across four instrument families – gas chromatograph, nuclear magnetic resonance spectrometer, ultraviolet spectrophotometer and the transmission electron microscope – von Hippel[42] found that nearly 80% of this development had been done by the users, the scientists, themselves. The story of technological jugaad and of the development of the indigenous STM in India then becomes even more interesting. The outcome (development of the instrument) may have been the same, but was the route followed similar to the one in the Indian case? What were the kinds of materials used in the creation of the instruments? Where were they sourced from? At what cost, if any?

Valuable insights can be gleaned in this context from another engaging account of the commercialization of scanning probe microscopy in Western Europe and USA. Mody[3,43] notes that in many instances of making these instruments there was a 'whimsicality (…) accompanied by bricolage in instrument building, [where STM] probes [were made] from pencil-leads [and] (…) AFM tips from hand-crushed, pawn-shop diamonds glued to tinfoil cantilevers with brushes made from their [researcher's] own eyebrow hairs'.

The point here is that this technological jugaad kind of innovation is not necessarily limited to the Indian context. It has worked (and still works) successfully in different parts of the world, including in the prominent centres of modern science and technology, albeit using a different vocabulary.

Characterizing technological jugaad

The above having been noted, the next step would be to create a more widely usable conceptual framework for technological jugaad. This, I attempt now with the help of seven characteristics that I have identified from the discussion above and extended inferences. These are presented here mainly as signposts; pointers that can help gain empirical research information and insights, and also guide and promote further discussion and research.

Reconfiguring materiality

One of the cornerstones of technological jugaad we have seen, be it the automobile in northern India or the STM in a modern physics lab – is the reconfiguration of materiality – giving new meaning to old objects and finding uses that they were not initially created for.

Problem-solving

Technological jugaad mainly involves finding a solution to an immediate problem. The immediacy of the problem is often linked to economic survival and may in a particular context, be an explicit manifestation of the imperative of continued existence. In that sense, then, it is different from invention or an activity of leisure such as pursuing a hobby.

Driven by resource constraints

One of the key conditions driving technological jugaad is resource constraint or denial. There is, therefore, no option but to find new meanings and uses for existing objects – a direct linkage to the first characteristic of reconfiguring materiality.

Bridging knowledge systems of ways of knowing

This paradigm of innovation, as we have seen, particularly in the case of the physics lab, embodies an important element of interdisciplinarity. There is an awareness of what is happening elsewhere and both the capacity and willingness to bring in ways of doing things that are located outside and, therefore, not considered part of the system.

Legally grey

The production process as well as the final object created, like in the case of the jugaad automobile in particular, might lie outside the existing legal framework – an area that maybe grey as far as the law is concerned.

Not (intended) for commercialization

Available evidence, although limited, suggests that commercialization is not the primary intention of jugaad, though there is no reason why it should not become successful commercially. In the first instance, however, it lies outside the broad framework of the marketplace.

A culture of recycling

There is a way of looking at waste; a culture of recycling that is central to the jugaad enterprise. This is about a society where resources are scarce and access is limited. There exist formal and informal systems where scrap and junk are indeed available as in the case of the junk markets that can be found in nearly all towns and cities.

Conclusion

It would also be relevant to mention here, particularly in the context of jugaad happening outside the laboratory, that a major chunk of the economic activity and employment in India is found in the informal sector[29,44], where there is no guarantee of employment and work and/or social security[44]. It is in this context of resource deprivation and/or denial that jugaad forms a lifeline for the livelihood and survival support-system of millions.

Technological jugaad might not perform precisely the same function inside a modern laboratory, but it is, undeniably, a part of the same continuum. It has the potential to energize and facilitate much of what Balaram[40] notes is sorely missing (or rapidly disappearing) from the laboratory. Sustaining and supporting it will, in fact, add much more to the S&T enterprise than it has been credited with and recognized for.

Notes

1. The other half of the prize was awarded to Ernst Ruska for his fundamental work in electron optics, and for the design of the first electron microscope.
2. He is presently visiting faculty at the Indian Institute Scientific Education and Research, Pune.
3. I would like to thank Rishikesha Krishnan for drawing my attention to this work by Pavan Verma. It is striking to note that Varma's exposition of jugaad appears not in the 'Technology' chapter in his book, but the chapter titled 'Wealth'. The 'Technology' chapter deals only with India's much discussed information technology sector.
4. The presentation was made at a national seminar on SPM at UoP that was organized to felicitate Dharmadhikari on his retirement.

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ACKNOWLEDGEMENTS. I have benefited immensely from discussions on jugaad and innovation I have had with a number of colleagues. I would like, in particular, to thank Ranjit Singh, Samir Passi, Esha Shah, Wiebe Bijker, Ragna Zeiss, Koen Beumer, Shambu Prasad, Annapurna Mamidipudi, Jyoti Bachani and Madhuvanti Anantharajan.

Received 12 June 2012; revised accepted 18 March 2013