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Searching for Asses, Finding a Kingdom: The Story of the Invention of the Scanning Tunnelling Microscope (STM)

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Summary

We offer a novel historical-philosophical framework for discussing experimental practice which we call 'Generating Experimental Knowledge'. It combines three different perspectives: experimental systems, concept formation, and the pivotal role of error. We then present an historical account of the invention of the Scanning Tunnelling Microscope (STM), or *Raster-Tunnelmikroskop*, and interpret it within the proposed framework. We show that at the outset of the STM project, Binnig and Rohrer—the inventors of the machine—filed two patent disclosures; the first is dated 22 December 1978 (Switzerland), and the second, two years later, 12 September 1980 (US). By studying closely these patent disclosures, the attempts to realize them, and the subsequent development of the machine, we present, within the framework of generating experimental knowledge, a new account of the invention of the STM. While the realization of the STM was still a long way off, the patent disclosures served as blueprints, marking the changes that had to be introduced on the way from the initial idea to its realization.

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> As he who, seeking asses, found a kingdom.
> John Milton (1671)
> *Paradise Regain'd*, 3: 242 (*Samuel* I, 9)

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1. Introduction: accounts of the invention of STM

Many writers have discussed different historical and philosophical aspects of the intriguing instrument, the Scanning Tunnelling Microscope (STM). They mostly concentrate on either the intricate philosophical issue of 'seeing' with the STM and the definition of this new kind of microscopy, or the development of the STM from a variety of perspectives, e.g. sociological, material settings, and instrumental constraints.[1] The concentration on either the historical account of the instrument or the philosophical issues which it poses originates in the division between history of science and philosophy of science. We offer an alternative framework for interpreting experimental practice and call it, 'Generating Experimental Knowledge'. We interweave in this framework three different perspectives: experimental systems, concept formation, and the pivotal role of error; this allows us to bring to bear both history and philosophy on the case of the STM. With the new interpretative scheme of Generating Experimental Knowledge, we tell the story of the invention of the STM in a novel way. After presenting a general account of the new framework, we proceed to analyse the case of the STM in which we distinguish three phases. We begin with the two patent disclosures which the inventors, Gerd Binnig (b. 1947) and Heinrich Rohrer (b. 1933), submitted in the late 1970s and early 1980s: the first on 22 December 1978, in Switzerland, and the second, on 12 September 1980, in the US.[2] These disclosures determined the blueprint of the instrument from the outset, while its realization—the second phase—was still a long way off. The story we tell expresses the tension between the original idea and making it work; the resolution of this tension—phase three—brought the two inventors the highest accolade in physics, the Nobel Prize (1986).

The first workshop on STM was held in Oberlech, Austria, 1–5 July 1985, under the auspices of IBM Europe Institute. Scientists from different laboratories presented many improvements, state-of-the-art designs, imaging techniques, and wider applications of the STM to diverse domains. The workshop reflected the growing interest in the STM. In the talk Binnig and Rohrer delivered, they spoke of several 'generations' of STM.[3] The two physicists thus turned into historians, reflecting on the stages leading to the successful machine. Indeed, later in their Nobel lecture, they presented, 'the historic development of Scanning Tunneling Microscopy'.[4] This is the first

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[1] H.C. Von Baeyer, *Taming the Atom. The Emergence of the Visible Microworld* (New York, 2000); A. Hessenbruch, 'Interview: Gerd Binnig and Heinrich Rohrer', in Binnig's office at IBM Zurich, Rüschlikon, 13:30–15:30, 4 May 2001 (3) in A. Hessenbruch, 'A short history of Scanning Probe Microscopy', Dibner's 'History of Recent Science and Technology' at: http://hrst.mit.edu/hrs/materials/public/STM, 2001; J. Schummer and A. Nordmann, eds., *Discovering the Nanoscale* (Amsterdam, 2004); Arne Hessenbruch, 'Nanotechnology and the Negotiation of Novelty', in Schummer and Nordmann, 135–44; D. Baird and A. Shew, 'Probing the History of Scanning Tunneling Microscopy', in Schummer and Nordmann, 145–56; J. Hennig, 'Changing in the Design of Scanning Tunneling Microscopic Images from 1980 to 1990', *Techné* 8 (2004), 1–20; C.M. Mody, *Crafting the Tools of Knowledge the Invention, Spread, and Commercialization of Probe Microscopy, 1960–2000* (Dissertation, Cornell University, 2004); C. Mody, 'How Probe Microscopists became Nanotechnologists', in Schummer and Nordmann, 119–33; C. Robinson, 'Images in Nanoscience Technology', in Schummer and Nordmann, 165–69; J.C. Pitt, 'The Epistemology of the Very Small', in Schummer and Nordmann, 157–63; J.Z. Buchwald, 'How the Ether Spawned the Microworld', in L. Daston, ed., *Biographies of Scientific Objects* (Chicago, 2000), 203–25.

[2] Patentschrift $_{\mathrm{A5}}$ #643 397, Gesuchsnummer: 8486/79; Raster-Tunnelmikroskop, Erfinder: G. Binnig, Richterswil, H. Rohrer, Richterswil, Schweizerisch-liechtensteinischer Patentschutzvertrag vom 22. Dezember 1978. US patent #4,343,993 for the Scanning Tunneling Microscope invented by G. Binnig and H. Rohrer, registered on 10 August 1982 (filed 12 September 1980). Since both patents, the Swiss and the American, are almost identical, all citations are taken from the American (English) version of the patent disclosure.

occasion—to the best of our knowledge—on which Binnig and Rohrer referred publicly to the patent disclosures:

> Mid-January 1979, we submitted our first patent disclosure on STM. Eric Courtens, then deputy manager of physics at the IBM Rüschlikon Laboratory, pushed the disclosure to a patent application with 'thousands of future STM's'. He was the first believer in our cause.[5]

We pay special attention to these technical documents. They are first and foremost legal papers, but they determined the scientific path—both theoretical and practical—leading to the construction of a successful machine. However, it is clear that the machine went through successive models, unforeseen in the disclosures.

In 1982, B. M. Schawrzschild, in a paper entitled, 'Microscopy by Vacuum Tunnelling', identified 'generations' of STM:

> The second-generation Zurich instrument, operating at room temperature and a vacuum of 5×10^{-10} Torr, has in fact already produced topographic 'pictures' of gold surfaces with a depth resolution of one or two tenths of an angstrom, clearly resolving monatomic steps.[6]

Thus, already in 1982, the idea of 'generations' as a historical concept was in the literature of STM. To be sure, it is common in engineering to refer to various successive models of a certain machine by 'generations'; this was most likely the practice in IBM, and Schawrzschild probably borrowed it from what he calls 'the Zurich group' (Binnig, Rohrer, Gerber, and Weibel).[7]

We adopt the term 'generation' as a useful notion for ordering the historical data, the several models of the STM; but unlike the inventors, we will set the 'generations' against the patent disclosures—the blueprint which determined from the outset the framework of this research. Although Binnig and Rohrer do not reflect in their technical papers on the various stages that led to the successful machine, they implicitly performed in these papers switches and advanced from one generation of STM to another. These 'switches' reflect the dual functionality of the STM. Binnig and Rohrer defined the machine they invented as a dual-purpose instrument: a microscope which executes spectroscopic investigations. We will discern then in the three phases of the story 'generations' of machines as well as 'switches' which constitute the engine of the transitions that characterize the development of this invention.

The inventors pursued a well-marked goal which had been designed in advance in great detail, and set down in patent disclosures. At each stage of their attempt at making their idea work, Binnig and Rohrer sought to obtain the means with which to build a machine along the lines of their theoretical plan. We study these developments within the framework of 'Generating Experimental Knowledge'.

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[3] G. Binnig and H. Rohrer, 'Scanning Tunneling Microscopy', *IBM Journal of Research and Development* 30 (1986), 355–69 (358).

[4] G. Binnig and H. Rohrer, 'Scanning Tunneling Microscopy—From Birth to Adolescence', Nobel lecture, *Reviews of Modern Physics* 59 (1987), 615–25 (615). The Nobel lecture was delivered on 8 December 1986.

[5] Ibid., 616.

[6] B.M. Schawrzschild, 'Microscopy by Vacuum Tunneling', *Physics Today* 35 (April 1982), 21–22 (22).

[7] Ibid., 21.

2. A novel methodological framework: 'Generating Experimental Knowledge'

It is undisputed that experimentation is a core procedure of the scientific enterprise. Indeed, it has for decades received the attention of historians, philosophers, and sociologists of science. New perspectives have been explored, but no comprehensive account has been achieved. We propose that the three elements which comprise what we call, 'generating experimental knowledge', namely, 'experimental systems', 'concept formation', and 'the pivotal role of error', are invariably engaged in the process of experimenting. We observe that, generally, experimental systems constrain the kinds of concepts that are formed in the attempt to comprehend the material setting under study, while the process of concept formation is in turn susceptible to failures and errors arising from the tenuous relation that holds between a certain concept and its material subject. Our proposed approach of generating experimental knowledge is designed to provide a better understanding of this complex epistemic structure and the associated dynamic of knowledge claims which are grounded in experiment. We suggest that this comprehensive approach towards experimentation can throw light on the story of the invention and development of the STM.

'Experimental systems' are essentially hybrid in their nature; they mix up elements—in varying ways—which historians, philosophers, and sociologists of science usually wish to have properly separated. This desire for separation is due to a vision of an epistemic purity that does not faithfully reflect the practice of science. In experimental systems, research objects, theories, technical arrangements, instruments as well as disciplinary, institutional, social, and cultural elements lead to amalgams of widely different composition. A philosophy of science that follows the dynamics of experimental systems is no longer concerned with dichotomies such as extrinsic versus intrinsic factors of scientific development, dominance of theory versus dominance of practice, basic science versus technical applications, or biographical-historical versus rational reconstruction. In this perspective, history of science becomes a history of epistemic things.[8] In the story of the STM, the experimental system comprises first and foremost the IBM frame of research, namely, an applied research into solid-state physics for the computer industry. Apart from the scientific research itself, the study of the case of the STM requires no doubt institutional as well as sociological analysis.

The next element in our approach is 'concept formation'. The invention of a new scientific instrument is always guided by some considerations that rely on basic instrumentation, procedures, and concepts that are regarded as stable and unproblematic. However, this process invariably takes place within a specific epistemic constellation in which the very array of stable elements is called into question and put to revision in the attempt at making the invention work with improved performance. This element is particularly instructive because acting and conceptualizing regulate one each other as the development of the instrument unfolds. Typically, such regulation calls for a revision of either the underpinning concept or the practice of executing the rule. Sometimes the formation of new concepts facilitates this execution. It is here, in the domain of concept formation, that exploration and probing are pursued. This requires openness to revising existing

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[8] H-J. Rheinberger, *Towards a History of Epistemic Things: Synthesizing Proteins in the Test Tube* (Stanford, 1997). M. Hagner, and H.-J. Rheinberger, 'Experimental Systems, Objects of Investigation, and Spaces of Representation', in M. Heidelberger and F. Steinle, eds., *Experimental Essays—Versuche zum Experiment* (Baden-Baden, 1998), 355–73.

categories and is therefore connected to a certain epistemic situation.[9] As we will see, in the case of the STM the instrumental system includes, already in the blueprint, the tunnelling unit for obtaining both spectroscopic results and images of metal surfaces—a new concept of microscopy which is based on the dual functionality of the instrument.

The third and the last element that contributes to 'generating experimental knowledge' is 'the pivotal role of error'. Like any goal-oriented procedure, experiment—the development of a new instrument may certainly be regarded as such—is subject to many kinds of error. They have a variety of features, depending on the particulars of their sources. For the experimenter and the inventor, these pitfalls should be avoided and their effects minimized. For the historian-philosopher of science, on the other hand, they are instructive points for reflecting on science in general and scientific practice in particular. Often more is learned from failure than from confirmation and successful application. That is, a failed experiment may provide new insights; a confirming experiment may add nothing to the theoretical framework. The identification of error, its source, its context, and its treatment shed light on both practices and epistemic claims. Understanding an error amounts, inter alia, to uncovering the knowledge generating features of the system involved—the very features that are the object of study of the historian-philosopher when it comes to evolving systems in scientific practice. The experimenter's suspicion that 'something is going wrong' and that 'something is not working', and indeed the recognition of an error is a pivotal element in concept adjustment and ultimately in securing stability in experimental systems. Thus, we study how precisely the recognition of different kinds of error affects the development and amendment of concepts in experimental practice.[10] In the story of the STM, we show that going back one step in the first phase of the development of the instrument, and then—in the second phase—two steps ahead, are the result of the ingenuity of the inventors who successfully negotiated a path from the epistemic framework, laid down in the blueprint, to the actual construction of the machine which required, among other things, the replacement of the crucial insulating system.

Each of these three frameworks has opened up new perspectives on experimentation. But knowledge generation encompasses all the three aspects: the evolution of experimental systems, the formation and revision of concepts that guide experimental action, and the specific role of error and failure in this process. Thus, only a multifaceted analytical framework can reveal the epistemological dynamic of the generation and grounding of knowledge in experiment. In this new approach, one conducts then a close and systematic examination of experimental error and failure, the experimenter's response to such obstructions, the adjustment of concepts in the face of recalcitrant obstacles, and, above all, the experimental system in which specific knowledge is being pursued and generated either through experimentation or, indeed, by the building of a scientific apparatus—in this case, the STM.

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[9] F. Steinle, 'Entering New Fields: Exploratory Uses of Experimentation', *Philosophy of Science* 64 (Supplement 1997), S65–S74; F. Steinle, (1998), 'Exploratives vs. theoriebestimmtes Experimentieren: Ampères erste Arbeiten zum Elektromagnetismus', ibid, Heidelberger and Steinle (1998), 272–97.

[10] G. Hon, 'Towards a typology of experimental errors: An epistemological view', *Studies in History and Philosophy of Science* 20 (1989), 469–504; G. Hon, '"If This Be Error": Probing Experiment With Error', note 8, Heidelberger and Steinle (1998), 227–48.

3. A new account: the three phases

3.1. *Phase one: the blueprint—patent disclosures of STM*

In 1978, Binnig and Rohrer of the IBM Zurich research laboratory studied the nature of Josephson junctions in the context of one of the commercial projects of IBM. A Josephson junction consists of the arrangement of two superconductors separated by a very thin oxide film. Binnig and Rohrer wanted to contribute to a better understanding of nanoscale inhomogeneity on surfaces of thin oxide films of Josephson junctions, and in particular its interference with attempts to obtain quantum tunnelling. The invention of a new kind of microscope was not on the agenda. This is the experimental system, the research framework within which the STM was eventually conceived and built.

The use of vacuum tunnelling for the purpose of studying oxide films came about in the fall of 1978 in discussions the researchers had had shortly before Binnig joined the laboratory in November of that year as a new staff member. The discussions revolved around the problem of how to study the films locally, and Binnig and Rohrer explicitly remarked that an 'appropriate tool' was lacking.[11] It took the two researchers a couple of weeks to realize that with a vacuum tunnelling unit, not only would they have a local spectroscopic probe, but that scanning would yield 'topographic images' of the inhomogeneities. The two researchers noticed that a dense collection of line scans formed in the two dimensional plane (x, y)—as a function of z—would exhibit certain images that could be interpreted as images of inhomogeneities.[12] Rohrer said later in an interview with Arne Hessebruch, 'You see, most things are new only because most people think it is wrong or impossible. That is why things can emerge as a novelty. Our case is not a singularity—it happens to many people.'[13]

Binnig and Rohrer associated the potential of imaging with a new kind of microscope. We characterize this realization 'the first switch'. It is akin to a Gestalt switch—seeing the instrument they were developing in a new light. The instrument could have dual functions: a spectroscope as well as an image-producing device. Binnig and Rohrer filed a patent of this new idea and announced that

> The object of this invention is to provide a new instrument for investigation of surface structures of highest resolution which utilizes the vacuum tunnel effect. Therefore, the apparatus is operating only with electrons bound by a potential. . . . These objects are met by the scanning tunneling microscope described herein.[14]

They stated,

> what we claim as new, and desire to secure by Letters Patent is:
> 1. Apparatus for investigating surface structures utilizing the vacuum tunnel effect, comprising:
>
> an ultra-high vacuum chamber which can be cooled down to a temperature close to absolute zero;
>
> a fine conducting tip and the sample surface;

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[11] Note 4, 615.

[12] Ibid.

[13] A. Hessenbruch, 'Interview: Gerd Binnig and Heinrich Rohrer', note 1.

[14] Note 2, 2.

> means for scanning said tip cross the sample surface ...
>
> means for graphically displaying the spatial coordinates of said scanning tip to produce a topological map of said surface.[15]

They remarked that their invention,

> relates to apparatus for investigation of surface structures utilizing the vacuum tunneling effect. An ultra-high vacuum chamber is cooled down to a cryogenic temperature in the vicinity of absolute zero. A conductive sample is placed in this UHV chamber and serves as a base electrode with respect to a fine conductive tip that serves as a scanning electrode. The scanning electrode is poised above the base electrode at a distance of only a few Angstroms.[16]

The key element is then a tunnelling unit with two conductors, one formed into the shape of a tip and the other serving as a sample surface. The sample acts as an electrode above which the tip is poised at a very short distance away, interacting with the sample through the tunnelling effect. The sample and the tip can be moved in three dimensions, relative to each other. Each electrode (the tip as well as the sample) are provided with piezo drives which operate in lateral dimensions, x and y. The piezo drive can act on the sample and move it relative to the tip. Alternatively, the sample may be fixed, and the drive may act on the tip. To function properly, this key element has to be insulated, and all vibrations must be suppressed; hence, the superconducting levitation system in an ultra-high vacuum (UHV) chamber (Figure 2, no. 52).

The piezo drive which holds the tip was invented by Binnig and his technician, Christoph Gerber, in 1979. While working within the framework of the Josephson project, Binnig and Gerber published their invention in an internal IBM journal. They designed the piezo drive in such a way that it could operate at low temperatures; they argued that it could carry a fine tip as a probe electrode. Binnig and Gerber sketched a Figure of this piezo drive, which was reproduced with no changes in the patents of 1978 and 1980.[17]

The Piezo drives that generate the motion of tip/sample relative to sample/tip are connected to a measuring device which in turn is linked to analysing means that is attached to a plotter and a viewing screen. The mechanical dimensions of the electrodes, sample and tip, as well as their possible ranges and adjustment are extraordinary small because of the delicate nature of the vacuum tunnelling effect (Figure 1, no. 4 and 5; Figure 2, no. 52).[18]

Data analysis is undertaken with respect to a three-dimensional representation. Both lateral, x and y dimensions, could be shown on a plotter or on a viewing screen device. For the third dimension, z, a suitable representation must be chosen. One possibility was to show the z values as steps of brightness at a point (x, y). Later transition from micrographs to greyscale images and false-colour images reflected this choice. Eventually, IBM personal computer systems were connected to the STMs, and that enabled Binnig and Rohrer to represent the z values; they then produced real-time, three-dimensional STM images. However, due to technical

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[15] Note 2, 12.

[16] Note 2, 1.

[17] G. Binnig and C. Gerber, 'Piezo Drive with Coarse and Fine Adjustment', *IBM Technical Disclosure Bulletin* 22 (1979), 2897; note 2, sheet 2 of 3.

[18] Note 2, 4.

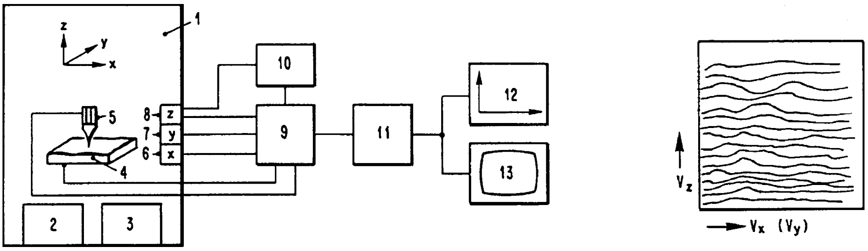

Figure 1. Block diagram of STM and a graphical representation of STM data as appeared in the patent disclosures of 1978 and 1980. With permission from IBM Zurich.

limitations in the original 1978 and 1980 patents, Binnig and Rohrer chose to represent the measuring values as a set of curves $x(z)$ which are a function of the parameter, y. They thus drew line scans in an x–y graph (Figure 1, right).[19]

Binnig and Rohrer claimed that their apparatus could perform raster scanning motions; that is, the sample surface is investigated in raster lines one after the other, and the whole image would be composed of the scanning lines of the scanning probe. The apparatus could produce images much like a scanning electron microscope. They thus called the instrument a 'Scanning Tunnelling Microscope'. According to Rohrer, the team called their instrument a Scanning Tunnelling Microscope already at the end of 1978.[20]

The key to Binnig and Rohrer's success was their adopted strategy of probing local surfaces down to the finest atomic scale. They discarded the common practice of measuring average distribution of aggregates of atoms and opted for local measurements—an essential step towards imaging atomic structures.

3.2. *Phase two: the struggle for realization—making the idea work*

The second phase started in 1981 and lasted until 1984. Binnig and Rohrer built the first prototype of the STM in 1981. They encountered technical problems and limitations: the scanning instrumentation was not fully developed, and the vibration suppression isolation system had many problems. Relying on the dual functionality of the design, they presented the first model as a vacuum tunnelling unit and spoke as vacuum-tunnelling physicists do when practising standard spectroscopy. By 1982, Binnig and Rohrer successfully modified a few elements of the machine; naturally, this conceptual reorientation was not detailed in the two patents of 1978 and 1980. Once they introduced the new technology, Binnig and Rohrer could finally make the machine work as a microscope. They called the modified instrument STM—the same name which they introduced in the blueprint. The second phase is characterized then by the successful realization of the patent disclosures which were constantly in the background, but were not referred to in Binnig and Rohrer's technical publications. This is the juncture where we see the working of the pivotal role of error in triggering a conceptual reorientation: divergence from the blueprint in order to overcome technical difficulties.

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[19] Note 2, 6.

[20] Private communication, H. Rohrer, 2 April 2006; note 2, 5; Binnig and Rohrer called their machine at the end of 1978, 'Raster-Tunnelmikroskop'.

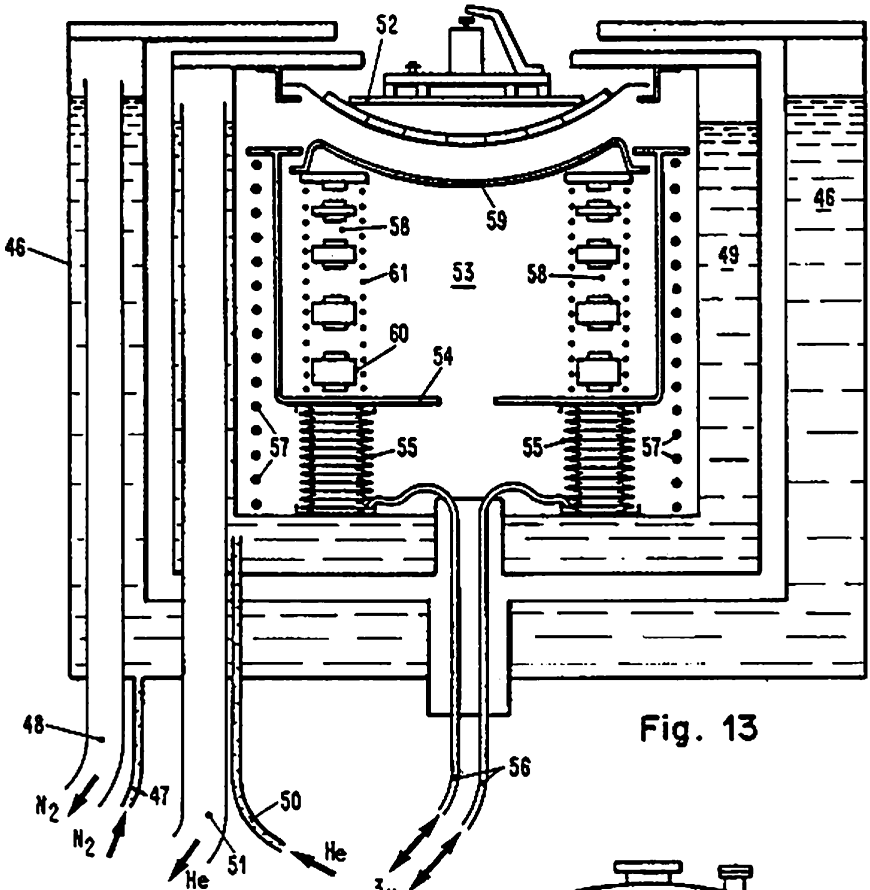

Fig. 13

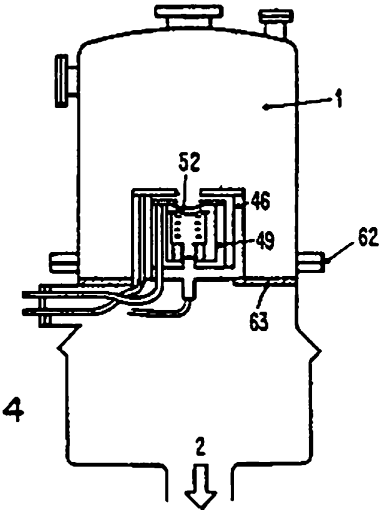

Fig. 14

Figure 2. Vertical section of the inner parts of the STM (figure 13, in Binnig and Rohrer's original figure) displaying the vibration-free suspension. The tunnelling unit, no. 52, is placed on the hovering support that must be free of vibration. The whole device is placed in an ultra-high-vacuum chamber (figure 14, in Binnig and Rohrer's original figure). The figures are taken from the patent disclosures of 1978 and 1980. With permission from IBM Zurich.

3.2.1. 1981, a step backward: problems with superconducting levitation

In 1980, Binnig and Rohrer asked Christoph Gerber, who had worked as a technician for some 15 years with Rohrer, to join their project as a technical assistant. About a year later, they recruited Eddie Weibel to the project as the second technician.[21] With the two technicians, Binnig and Rohrer formed a small group, which was later called the 'Zurich group', and the instrument they were working on was referred to as 'the Zurich vacuum-tunneling junction'.[22] The instrument was in fact an STM which was built according to the blueprint drawn in the two patent disclosures of 1978 and 1980: a tunnelling unit insulated by a superconducting levitation system that was based on low-temperature instrumentation.

Construction and low-temperature tests as well as UHV trials took a year. Naturally, the Zurich group tried at first to build the apparatus as it was described in the patent disclosures. However, they encountered difficulties, and the apparatus that they actually built in 1981 was a vacuum-tunnel junction which consisted of a platinum plate and a tungsten tip about 1 mm in diameter (Figure 3). The elements of the tunnelling unit were in fact of simpler and inferior state than the intended plan. The sharp tip could be moved with a piezo-drive towards the plate until contact by applying the device which Binnig and Gerber invented in 1979.[23] Fine control of the electrode distance in the *z* direction, and relative to the *x–y* position of the electrodes was achieved by the piezo-drive, to which the platinum plate was fixed. The tip was mounted on a support whose driving mechanism consisted of a piezo-plate, resting with three metal feet on a metal plate, insulated from each other by a dielectric material. The feet could glide freely on the dielectric, or be clamped in place by applying a voltage between the feet and the metal plate. Elongation and contraction with an appropriate clamping sequence of the feet allowed movements of the support in any direction in steps down to 100 Å. The Zurich group built a glass platform for this mechanism, which they later called 'louse'. In fact, the whole instrument looked rather like a glass pot (Figure 3).

In the original patent disclosures, Binnig and Rohrer suggested building a scanning unit in which *both* the tip and the plate were provided with piezo drives *x*, *y*, *z*. Thus, according to the blueprint, the piezo drives would act on the plate and move it relative to the tip, or the plate could be fixed, and both lateral piezo drives could act on the tip. However, when the STM group built the first instrument, only the tip was provided with the means to act on the plate.

Other limitations were more crucial. There were many problems with the superconducting levitation system. In effect, Binnig and Rohrer used a primitive version of superconducting levitation held with Scotch tape and wasting about 20 l of liquid helium per hour.

The group had to solve another serious problem. In the patent disclosures, Binnig and Rohrer thought that they could build a UHV chamber that includes means for generating a high vacuum: 'The apparatus must operate in an ultra-high vacuum of better than 10^{-10} Torr.'[24] In practice, their setup allowed only a vacuum down to 10^{-6} Torr.[25] The result was that Binnig and Rohrer built a vacuum-tunnel junction and not a microscope. Their construction could not yield images.

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[21] Note 4, 616–17.

[22] Note 6, 21.

[23] See note 17.

Figure 3. Tunnelling unit (first-generation STM) built by the Zurich group in 1981 according to the patent disclosures of 1978 and 1980: glass platform and glass shield for what would later be called a 'louse', and an *x–y–z* piezodrive that could not yet perform proper scanning motions. Photograph by G. Granek.

On 16 March 1981, the STM group obtained a clear exponential dependence of the tunnel resistance as a function of the tip–sample gap, in complete accordance with the vacuum tunnel theory as it had been developed in quantum mechanics. They published the graphs to show that indeed their apparatus was a 'vacuum-tunnel junction'.[26] The group published the first account of their instrument under the name vacuum-tunnel junction; they did not call it then an STM. They presented their instrument as a tunnelling unit that was shielded from vibrations by a superconducting levitation system in a UHV chamber. Binnig and Rohrer published two papers explaining how their new vacuum tunnelling unit could be used to study the surface properties of the tunnel electrodes of superconducting tunnel junctions.[27]

Rohrer later recalled in the interview with Hessebruch:

> That was the second stage. I mean we have just been talking about the first stage, in 1981–1982, when surface science was not even in the picture. We were simply demonstrating vacuum tunneling in an STM configuration: with a tip and a sample that could be moved around. The configuration was similar to the one in the second stage where we began to create images. But during this first stage we did not produce any images, and hence surface science was not in the picture. We were just discussing vacuum tunneling. Surfaces came into play once we created images.[28]

Following this successful demonstration of vacuum tunnelling with the new machine, Binnig and Rohrer's way of thinking about their instrument underwent a

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[24] Note 2, 2.

[25] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, 'Tunneling Through a Controllable Vacuum Gap', *Applied Physics Letters* 40 (1982), 178–80 (178) (received 30 September 1981).

[26] Note 4, 618.

[27] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, 'Vacuum Tunneling', *Physica* 109 and 110B (1982), 2075–2077 (originally a talk, 19–25 August 1981) (2075). For the second paper, see note 25.

second change. In August 1981, 'after this first important step with a complete STM set-up, it took us only three months ... to obtain the first images of monosteps on $CaIrSn_4$ [Calcium–Iridium–Tin] single crystal'.[29] However, they did not publish the complete results; they explained this hesitation in their Nobel lecture.

> Our excitement after that March night was quite considerable. ... Gerd immediately wanted to submit a post-deadline contribution to the LT16 Conference to be held in Los Angeles in September. He was going there anyway ... and I was sure he would have some topographic STM images by then. And indeed we had [presumably the micrographs of the sample $CaIrSn_4$]. I arranged an extended colloquium tour through the USA for Gerd, but about three weeks before his departure, a friend warned him, that once the news become public, hundreds of scientists would immediately jump onto the STM bandwagon. They did—a couple of years later.[30]

Binnig attended the LT16 conference. He presented the 'vacuum-tunnel junction' and the function graphs that the group had obtained back in March.[31]

We discern, however, a tension between the historical account that Binnig and Rohrer presented in their papers in 1896 and the actual early technical reports of 1981 and 1982 on the results which the two inventors had obtained with the first vacuum tunneling unit. In 1982, Binnig and Rohrer remarked that the device yielded the image of $CaIrSn_4$ with one STM and then the gold (Au) topographies with an improved STM:

> *$CaIrSn_4$*— ... good candidates for testing the operation of the STM at moderate vacuum ($\approx 10^{-6}$ Torr). ...
> *Au*—The Au pictures were taken with a new, improved tunnel unit with considerably increased stability. ... After Ar sputtering and subsequent annealing at 600°C in (2 to 7) $\times 10^{-10}$ Torr. ...[32]

Recall that in the patent disclosures, Binnig and Rohrer thought that they could build an STM that would operate at a vacuum better than 10^{-10} Torr.[33] In practice, in 1981, their STM operated only at a moderate vacuum of 10^{-6} Torr.[34]

What then is this 'improved STM'? An STM operating at vacuum better than 10^{-10} Torr? Since the authors did not speak then in the language of 'generations', we do not know. Indeed, we do not know how many machines the Zurich group in fact built. It stands to reason that they passed in silence over a few unsuccessful, so to speak 'in-between', machines and chose to concentrate on three or four models and refer to them later, from the podium of the Nobel lecture, as 'generations'. In 1986, Binnig and Rohrer noted that they had obtained topographic images of the $CaIrSn_4$ with the first generation STM. These are no doubt recollections, and should be considered as such when taken as historical sources. It may well be possible that the two inventors performed some primitive imaging with the machine they had built in

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[28] A. Hessenbruch, 'Interview: Gerd Binnig and Heinrich Rohrer', note 1, 4.

[29] Note 4, 619.

[30] Ibid, 615.

[31] For the LT16 Conference lecture, see note 27; it was published in 1982.

[32] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, 'Surface Studies by Scanning Tunneling Microscopy', *Physical Review Letters* 49 (1982), 57–61 (58–59) (received 30 April 1982).

[33] Note 2, 2.

[34] Note 25, 178.

1981. They probably obtained some blurred line scans of the $CaIrSn_4$. Indeed, in 1982, they reported that the quality of these line-scans was so poor that they had to draw in-between lines to enhance the visibility of the image. 'For better visualization of the topography of the surface some additional lines have been interpolated (broken) between the smoothed scans.'[35]

It is most likely that this is the reason why they did not present these images in the LT16 Conference held in Los Angeles in September, 1981. The images were not convincing, and the community could have responded by claiming that the 'Topografiner', or any older machine, could do much better. Binnig and Rohrer preferred to play it safe and improved first the performance of their machine before presenting the results to the community. And so it was; when, in 1982, they published the 'shiny image' of the silicon, in which one could see 'topography' of atomic surface in a very high resolution, the community of surface science responded with great enthusiasm. There was no need then to encourage the practitioners to 'jump onto the STM bandwagon'—they did it on their own.

3.2.2. 1981–1982, two steps forward: a new insulating system

Experimenting further with their construction, the Zurich group realized that the superconducting levitation might be unnecessary after all.[36] The inventors changed the original plan of superconducting levitation to a simpler new protector, a two-coil spring system with eddy-current damping, which was then incorporated into a UHV chamber. The tunnelling unit of the instrument consisted of a 'tripod' three arm *x–y–z* scanner which moved the tip and performed the scanning motion mechanically. In addition, a device was introduced which the group called 'louse'. This was responsible for the delicate approach of the tip to the sample. The 'louse' was based on the driving mechanism which rested on three metal feet that moved the tip in the first generation STM. The instrument was compact in comparison with the machine of 1981. The apparatus was now capable of performing proper raster scanning motions. The STM group finally built a 'microscope' and, in their publication of 30 April 1982, called this second-generation machine, a 'Scanning Tunnelling Microscope', as they had already done in the patent disclosures (Figure 4).[37]

The inventors now presented the STM as an instrument belonging to scientific studies in general, and surface science in particular, and not as an 'appropriate tool' for solving technical problems in IBM products. They finally published the micrographs of the sample $CaIrSn_4$ and added micrographs of gold and silicon which they produced with the new instrument. These new surface studies had nothing to do with the Josephson project. Binnig and Rohrer solved with the new instrument longstanding problems in surface science, for example, the problem of the exact atomic structure of the $Si7 \times 7(111)$ surface (Figure 5). They thus created a new interdisciplinary field in physical chemistry. Binnig and Rohrer published two additional papers on the new STM and the image of $Si7 \times 7(111)$.[38]

In 1985, Binnig and Rohrer called their first apparatus of 1981 the 'first-generation STM', and they referred to their second instrument of 1982 the 'second-generation STM'.[39] They thus considered in retrospect the first machine which they

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[35] Note 32, 59.
[36] Note 4, 619.
[37] Note 32, 57–60.

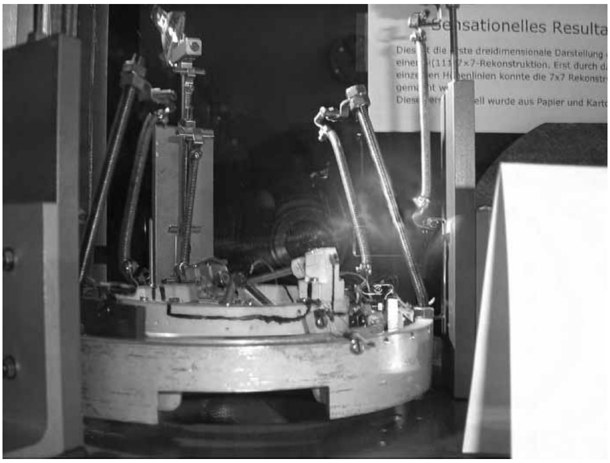

Figure 4. Second-generation STM; vibration shielding with steel springs, and vibration damping by eddy currents. Photograph by G. Granek.

had built in 1981 with Gerber and Weibel a ‘first generation STM’, even though it functioned only as a vacuum tunnel junction. In 1985, they called this machine ‘STM’ because it was supposed to be a replica of the design that had appeared earlier in the patents of 1978 and 1980, a design named ‘scanning tunnelling microscope’.

In his interview with Binnig and Rohrer, Hessenbruch asked the two inventors: ‘The first paper you submitted was rejected, right?’[40] Rohrer replied, ‘No, that’s not really correct. The first paper we submitted was a paper for the low-temperature conference where you [to GB] gave the post-deadline paper. Or did we submit the other one to *Physics Review Letters* before?’[41] Binnig agreed: ‘I think before, yes. And that was rejected’.[42] Hessenbruch then asked the two researchers what was the reason for the rejection of the paper? Rohrer reported that one ‘referee more or less said that it was not interesting, because everybody knows that a tunneling current is an exponential function. I think he did not get it’.[43] And Binnig added: ‘He missed the point. In the paper, we did explain what it might be used for, but he did not understand it’.[44]

Binnig and Rohrer did explain ‘what it might be used for’, but only towards the end of their second paper. The reader of Binnig and Rohrer’s second paper understood that the authors found the solution to the longstanding problem: how to build a vacuum tunnelling unit. No imaging is mentioned. Binnig and Rohrer performed experiments with the new machine, demonstrating that indeed their instrument was a working vacuum tunnelling unit. But what about microscopy? This was hinted only towards the end of their paper:

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[38] G. Binnig and H. Rohrer, ‘Scanning Tunneling Microscopy’, *Surface Science* 126 (1983), 236–44 (received 30 September 1982). G. Binnig and H. Rohrer, ‘Scanning Tunneling Microscopy’, *Helvetica Physica Acta* 55 (1982), 726–35 (received 30 December 1982).

[39] Note 3, 358.

[40] A. Hessenbruch, ‘Interview: Gerd Binnig and Heinrich Rohrer’, note 1, 2.

[41] Ibid., 3.

[42] Ibid.

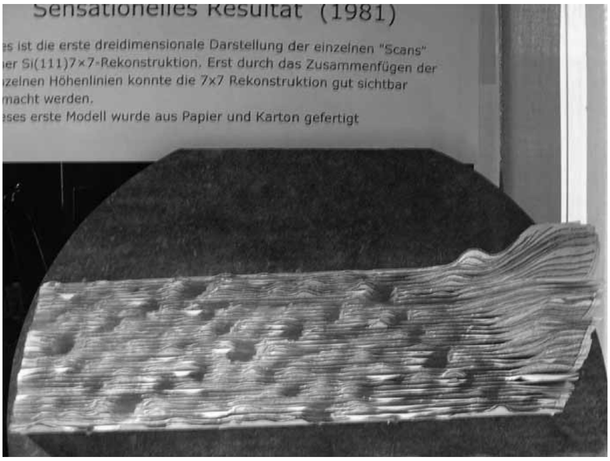

Figure 5. Si7 × 7(111) image. The silicon reconstruction was considered the greatest puzzle in surface science. It was first observed in 1959 with Low Energy Electron Diffraction (LEED). The LEED experiments revealed the general arrangement of the atoms, yet were incapable of discerning the details of the arrangement of these atoms due to the averaging character of LEED. The missing information was filled in during the 1960s and 1970s by theoreticians who suggested many contradictory models, none of which could be determined conclusively by experimental means. This problem remained unsolved in spite of many hints from a great number of surface techniques. STM solved the problem. Photograph by G. Granek.

> In summary, we have shown that vacuum tunneling with externally controllable tunnel distance is technically feasible, even at room temperature and nonultrahigh vacuum conditions. This investigation is the first step towards the development of scanning tunneling microscopy, where the surface is scanned by a tunnel current and should open the door to a new area of surface studies.[45]

The Zurich group ended their first paper by saying exactly the same thing. Alas, not explaining ‘what it might be used for’.

> In summary, we have shown that vacuum tunneling with controllable tunnel distance is technically feasible, even at room temperature and non-ultrahigh vacuum conditions. This should open the door to a new area of surface studies.[46]

In the two patent disclosures of 1978 and 1980, Binnig and Rohrer were much ahead of their technological capabilities so that when they began building the machine, they had to go a step backward. But given the microscopy terminology in the patent disclosures and the Figures showing graphical line scans, it appears that all the required elements were in the patents right from the outset; only the technology was missing. In 1981, the first instrument was built exactly according to the blueprint of

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[43] Ibid.
[44] Ibid.
[45] Note 25, 179.

the patents, but the vibration isolation system did not function properly, and the scanning unit was not fully developed. After 1981, a few critical, technological modifications in the design were implemented. The first change led to the instrument of 1982 which had a vibration isolation system that did not appear in the patents. Binnig and Rohrer therefore did not call the first instrument, STM—it did not produce images. They, however, called the second instrument STM, like the instrument described in the original patent disclosures.

3.2.3. Change of terminology: from tunnelling physics to microscopy

But there is more to the story. We may further ask: Is there a switch in terminology? Already, in the blueprint Binnig and Rohrer described a tunnelling unit using the terminology of microscopists. They considered the original design of the STM a contribution to contemporary microscopy; indeed, they compared the new device to different microscopes. They noted that 'the tunneling microscope has a kind of "focus" with a radius of about 50 Å (5 nm)'.[47] They also suggested that the STM should have the highest resolution ever achieved, and defined the STM as a new microscope for atomic imaging:

> A well known method for investigation of surface structures is by visual inspection with the human eye. However, there are natural boundaries for optical resolution with the naked eye. Optical instruments can be used to further improve optical resolution. However, even with the best optical instruments, limits are reached which are imposed by the nature of light.
>
> Resolution can be further improved using apparatus operating with radiation of effective wave-length which is shorter than visible light, such as the electron microscope. However, more complicated apparatus is needed because an electron microscope operates in a vacuum and the results of the inspection must be made visible on a screen or photosensitive layer. In comparison with optical microscopes, lateral resolution is improved remarkably. However, vertical resolution again soon reaches a limit.[48]

And they continued to define microscopy.

> The term microscopy is used where a surface is imaged with radiation of the same energy. Where radiation of different voltages of frequencies is used, i.e., with varying energy, the term spectroscopy is generally used. Dual purpose instruments are usually called microscopes even if they allow spectroscopic investigation as well.[49]

This definition arose in the Gestalt switch that Binnig and Rohrer had undergone: seeing the instrument in a new light. Vacuum tunnelling could serve as an 'appropriate tool' for studying inhomogeneities, giving *at first* spectroscopic information. Binnig and Rohrer then discovered that their machine could yield images and thus function also as a microscope. However, in the two patent disclosures, they reversed the order of the definition: an instrument which is in the first place a microscope, 'even if' it functions as a spectroscopic probe 'as well'.

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[46] Note 27, 2077.

[47] Note 2, 4.

[48] Ibid., 1.

The two patents exhibit a design which has a dual functionality: it could function as a microscope as well as a vacuum-tunnel junction. For Binnig and Rohrer, a microscope was an instrument that images a surface with radiation of the same energy. With the change of energy, the instrument turned into a vacuum-tunnel junction. This duality became a kind of trap when, in 1981, the first-generation STM was built. Only the 'varying energy' option could be exploited. Binnig and Rohrer and their technicians were unable to use the option of the 'same energy' due to technical problems in the vibration isolation system.

In the patent disclosures of 1978 and 1980, Binnig and Rohrer considered their invention a member of the family of traditional microscopy. Confident enough, they decided that their instrument was a microscope by definition. One therefore could use microscopy terminology in order to describe the STM and its elements. They remarked that their instrument has the highest range of resolution: 'This new scanning tunneling microscope exhibits an extraordinarily good resolving power'.[50] In the two patent disclosures, they presented a Figure that compares the limits of resolution of some microscopes with the human eye (Figure 6).

Lateral resolution is indicated along the abscissa and is in the range of 10^9 Å through 1 Å (10^8 nm through 0.1 nm). The ordinate corresponds to vertical resolution in the range of about 10^9 Å through 10^{-2} Å (10^8 nm through 10^{-3} nm). The resolution limits (23) of the human eye are shown lying in the range of about 10^9 Å through 10^6 Å of vertical resolution. Roughly three power ranges of microscopes may be defined:

1. (24)–(28): different kinds of optical microscopes. (24)—low-power optical microscopes. (25)—high-power optical microscopes (HM). (26)—multiple-beam interferometers. (27)—phase-contrast microscopes (PCM).
2. (29)—electron microscopes: cover the largest range of lateral resolution as yet available. (30)—the scanning electron microscope (SEM) is better with respect to vertical resolution.
3. (31)—the STM: achieves a vertical resolution that 'has not been achieved yet by any other instrument'.[51]

However, when Binnig and Rohrer and their two technicians built the first generation STM in 1981, they no longer spoke in terms of microscopy: 'focus' or 'resolution' is nowhere to be seen. The adopted terminology was that of vacuum tunnelling physics.

> The concept of tunneling in solid-state physics first appeared in context with tunneling into vacuum or through a vacuum barrier. On the one hand, tunneling as a spectroscopic tool was developed exclusively for solid tunnel barriers. Experimenters using vacuum tunnel barriers, although often attempted, have been unsuccessful mainly because of vibration problems. This is rather regrettable, since the interest in vacuum tunnel barriers is evident:

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[49] Ibid. For the original German, see note 2, 2–3 (patent 1978): 'Bei einer Abbildung der Oberfläche mit gleich-energetischer Strahlung spricht man von Mikroskopie. Im Falle einer Untersuchung mit Strahlung unterschiedlicher Spannung oder Frequenz, d.h. mit variierender Energie, spricht man im allgemeinen von Spektroskopie. Dennoch nennt man die Geräte meist Mikroskope, auch wenn sie zusätzlich spektroskopische Untersuchungen ermöglichen'.

[50] Ibid., 9.

[51] Ibid.

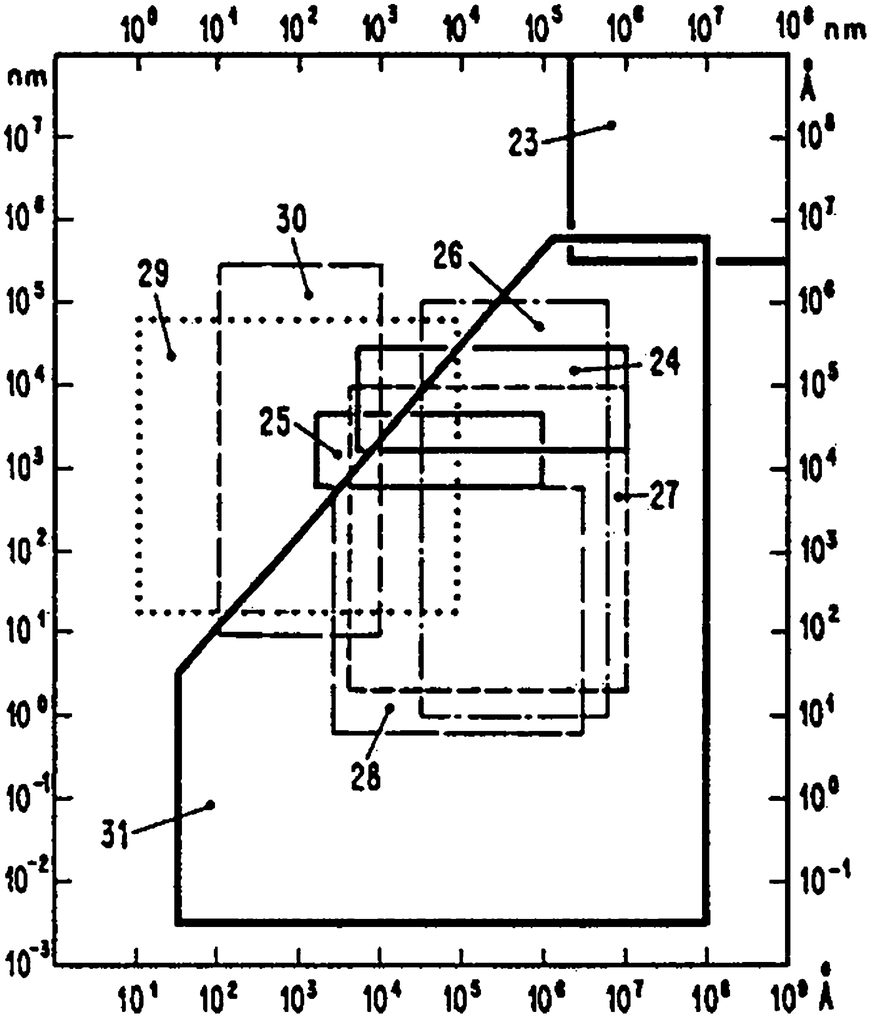

Figure 6. Comparison of the resolution limits of various microscopes as displayed in the patent disclosures of 1978 and 1980. 24–28: different kinds of optical microscopes; 29: electron microscopes and the highest resolution that could be achieved, the scanning tunnelling microscope (31). The latter covers the whole range of 10^8 Å to 10^2 Å lateral, and 10^7 Å to 10^{-1} Å vertical. Binnig and Rohrer underlined that vertical resolution such as this has not been achieved yet by any other instrument. With permission from IBM Zurich.

> conceptually most simple barrier, free access to the electrodes for other investigations of physical and chemical processes, e.g. in connection with inelastic tunneling spectroscopy. The possibility of vacuum tunneling opens an interesting and challenging new area of surface investigations.[52]

By 1982, as the Zurich group gradually developed the units of the apparatus to become the second generation STM, the group members began considering interpretative conventions for the images that the STM began producing. The transformation of the instrument into a microscope led the Zurich group to adopt a topographic terminology and to interpret the images as 'valleys' and 'hills' in some topography—the surface of the metal. For instance, they described their images first as 'sequences of double-maximum-double-minimum and single-maximum-single-minimum ... structures'.[53] Then, they characterized the same structures in terms of topographical notions: 'The valleys ... narrow valleys'.[54] They concentrated on interpreting the created images and thereby gradually inaugurated an STM tradition.

The switch in terminology marks the development of the second generation STM. The inventors could now return to the original language of microscopy which they used in the patent disclosures. In 1982, Binnig and Rohrer finally had a working microscope, and so they compared it to different microscopes in the same manner as they had done in the blueprint. They aimed at including the STM within the microscopy family.[55] Binnig and Rohrer reproduced the Figure from their 1978 and 1980 patents (Figure 6, above), and published it in their *Helvetica Physica Acta* paper of 30 December 1982 (Figure 7).[56]

The Figure of 1982 (Figure 7) compares the limits of resolution of various microscopes: STM is represented by the shaded area; HM: high-resolution optical microscope; PCM: phase-contrast microscope; (S)TEM: (scanning) transmission electron microscope; SEM: scanning electron microscope; REM: reflection electron microscope, and FIM: field ion microscope. Notice that the resolution limits of the STM in Figure 7 are higher than the resolution limits in Figure 6. Thus, the resolution of the STM was improved dramatically in its second generation; the device in action advanced beyond the theoretical expectations set down in the blueprint. In fact, Binnig and Rohrer pointed out that 'an inherent limitation of the STM is that it always operates at high resolution'.[57] They ended their *Helvetica Physica Acta* paper with the following remark: 'However, we should like to point out that we understand the STM as a complement to present microscopy rather than a competitor. For many applications, the STM is best used in combination with another microscope.'[58] The two inventors thus made it clear that the great vertical resolution of the STM has to be complemented with other microscopic, horizontal observations.

3.3. *Phase three: triumph—first perspective on the history of the STM*

In the third phase, from 1984 onward, the gates opened: advance and expansion of STM techniques by different laboratories with competing designs. As Binnig and Rohrer phrased it, 'the STM's "Years of Apprenticeship" have come to an end, the fundamentals have been laid, and the "Years of Travel" begin'.[59]

Already in the patent disclosures of 1978 and 1980, Binnig and Rohrer mentioned that in the upper part of the UHV chamber, there was sufficient room for other surface structure investigative instruments, in addition to the STM.[60] The paper in *Helvetica Physica Acta* of 1982 led Binnig and Rohrer to the construction of the third- and

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[52] Note 25, 178.

[53] G. Binnig, H. Rohrer, C. Gerber, and E. Stoll, 'Real-Space Observation of the Reconstruction of Au(100)', *Surface Science* 144 (1984), 321–35 (325).

[54] Ibid.

[55] Note 38, 734.

[56] Ibid.

[57] Ibid.

[58] Ibid.

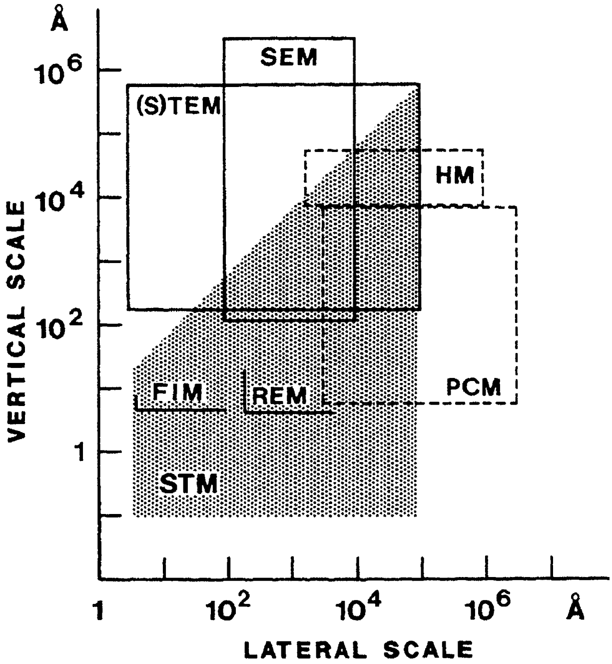

Figure 7. A similar figure to Figure 6 reappears in a paper published in 1982, after Binnig and Rohrer had built their second-generation STM. However, the resolution limits in this figure are higher than the resolution limits in Figure 6. The resolution of the STM increased dramatically (as can be seen in the figure) when it became operational.

fourth-generation STM in which they combined the STM with other traditional microscopes. Binnig and Rohrer built the third-generation instrument that had the appearance of a tower-like structure made entirely of quartz; no changes were made in the scanning tunnelling unit and in the vibration suppressor. This STM had a very large, complicated, and massive vibration isolation system. Indeed, to use the STM together with other surface-analytical tools, would require large UHV systems. To some scientists, it seemed that the unnecessary complexity of the first generation STM had somehow returned; they called this structure the 'quartz tower' (Figure 8).[61]

In a private communication, Rohrer commented that this third generation of STM was 'a monster of an instrument, a glass scaffold in order to have the sample for additional LEED investigation well separated from the eddy current damping magnets'.[62]

By 1985, the Zurich group understood that if one wanted to incorporate the STM with a conventional Scanning Electron Microscope (SEM) or combine it with other UHV analytical tools, then the STM had to be smaller. Such a combination would make use of both the ultrahigh resolution and the versatility of STMs as well as the established merits of SEM; this would allow the same sample surface to be imaged by

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[59] Note 4, 623.

[60] Note 2, 12.

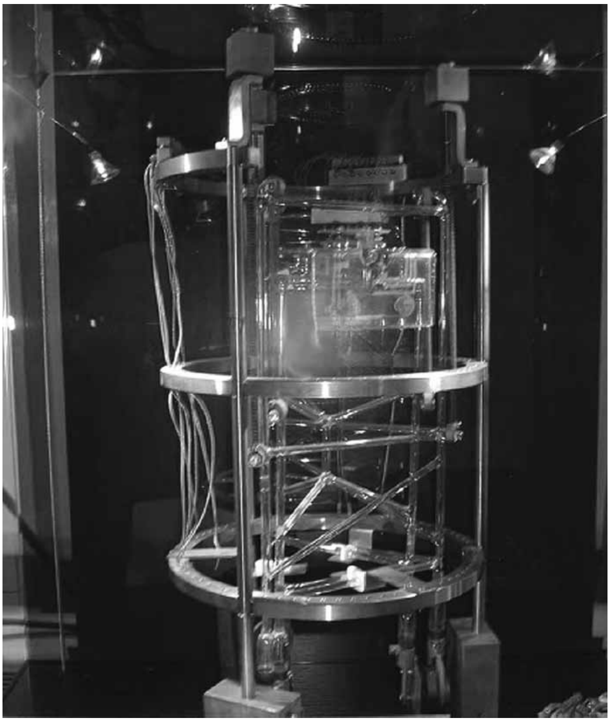

Figure 8. Third-generation STM: the quartz tower. Photograph by G. Granek.

the STM and the SEM. The Zurich group noted, 'this was the main motivation to develop a "pocket-size" STM'.[63] They found that replacing the coil springs by rods did not dramatically undermine the vibration-isolation properties.

Together with O. Marti and H. Fuchs, the Zurich group built their fourth-generation STM with a vibration-isolation system. It consisted of a stack of stainless-steel metal plates separated by UHV-compatible rubber pieces: three (or more) 'viton' dampers in between each pair of stainless steel plates. The top metal plate carried the scanning tunnelling unit. This pocket-sized STM was incorporated in a UHV SEM chamber. The STM turned into an economical, 'black box' instrument. This was the first step towards simplification of the instrument; it opened the road to the commercialization of the new machine. Rohrer remarked later that the fourth generation went back 'to compact instruments for more flexible use with less space available. Some with spring vibration shielding, some with just a stack of rubber dampers . . . and some along other lines'.[64]

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[61] C.F. Quate, 'Vacuum Tunneling: A New Technique for Microscopy', *Physics Today* (August 1986), 26–33.

[62] H. Rohrer, private communication to the authors, 20 September 2006. Low Energy Electron Diffraction (LEED) is a technique used to characterize the structures of surfaces (see also Figure 5, caption).

[63] G. Binnig, H. Fuchs, C. Gerber, O. Marti and H. Rohrer, 'Scanning Tunneling Microscope combined with a scanning electron microscope', *Review of Scientific Instruments* 57 (1986), 221–24 (221) (received 17 July 1985).

The STM was presented to the general public in 1985, in a paper published in the popular journal, *Scientific American*. In this paper, Binnig and Rohrer displayed a shining image of the surface of the Si (111) 7 × 7. They further described the fantastic imaging capability of the instrument. Binnig and Rohrer remarked proudly, 'our microscope enables one to "see" surfaces atom by atom'.[65] Yet, in their technical papers, they emphasized time and again that the 'STM senses *electronic* surface configurations rather than atomic positions'.[66] But one does not quibble with success, and a success the STM has been.

In 1986, the first international conference on STM (STM'86) was held in Spain. This was the first open conference on the STM after the first IBM workshop on STM held in 1985 at Oberlech, Austria. It was not clear whether the STM technique had matured and spread out enough for organizing an open conference. However, over 200 participants and more than 60 papers made it amply clear that the STM had struck roots in the physics community.[67]

In this atmosphere of success, the Nobel Prize committee awarded the 1986 prize in physics to the STM inventers, Binnig and Rohrer. (They shared the prize with Ernst Ruska for his design of the electron microscope.) In their Nobel lecture, there is a Figure of the fourth-generation STM and a description of its 'simple and presently widely used vibration protection'.[68] In a private communication, Rohrer confirmed the development of the STM in four 'generations'. He remarked that 'each "generation" had its distinct new features, that is probably why we used among us the expression "generations"'.[69]

4. Conclusions

Binnig and Rohrer put forward the conception of the STM in two separate but similar patent disclosures which they filed first by late 1978, in Switzerland (in German), and then some two years later in the US (in English). The two inventors had at the outset of their research a detailed blueprint that stipulated goals and means which determined how the research proceeded. They had described the functioning of the device more than a year before they actually began realizing it, and ingeniously foresaw the microscopic capabilities of the vacuum tunnelling unit.

With hindsight, using Binnig and Rohrer's so-called 'historical' nomenclature, we can tell the story of the blueprint of the STM and its realization in three phases. In 1981, Binnig and Rohrer demonstrated successfully vacuum tunnelling. They established the function 'voltage vs. distance' with what they called in 1986 the 'first generation' STM. However, this first prototype had substantial technical problems, notably the vibration isolation system. Binnig and Rohrer realized that their plan for such a system, which was based on superconducting low-temperature technology,

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[64] Note 62.

[65] Gerd Binnig and Heinrich Rohrer, 'The Scanning Tunneling Microscope', *Scientific American* 253 (1985), 40–46 (on 40).

[66] A.M. Baro, G. Binnig, H. Rohrer, E. Stoll, A. Baratoff, and F. Salvan, 'Real-Space Observation of the 2 × 1 Structure of Chemisorbed Oxygen on Ni(110) by Scanning Tunneling Microscopy', *Physical Review Letters* 52 (1984), 1304–1307 (1305).

[67] N. Garcia, ed., 'STM'86 Proceedings of the First International Conference on Scanning Tunneling Microscopy' (14–18 July 1986, Santiago de Compostela, Spain), *Surface Science* 181 (1987).

[68] Note 4, 617.

[69] Note 62.

could not be realized because this technology was not fully understood at the time. They therefore presented their first machine as a vacuum tunnelling unit and spoke as vacuum tunnelling physicists do. This concludes the first pioneering phase.

In the second phase, the inventors discarded the awkward and clumsy vibration isolation system and conceptualized a new one. For obvious reasons, this is not found in the two patents of 1978 and 1980; clearly, the two researchers felt the need to depart from the blueprint and reorient themselves conceptually. The new isolation system comprised double springs and eddy current magnets which suppressed the vibrations. The two inventors note in their Nobel lecture that after March 1981, they obtained topographic images with an improved STM. They did not publish these images because they suspected that the images are not convincing enough.

In 1986, Gerber, Binnig, Fuchs, Marti, and Rohrer described retrospectively the history of the STM: 'In the first ... [generation], we used superconducting levitation as vibration isolation. The gap-width stability was sufficient to resolve nanoatomic steps on $CaIrSn_4$'.[70] They then referred to the paper they published in 1982 in the *Physical Review Letter* (*PRL*) in which these line scans are presented for the first time.[71] In this paper, Binnig, Rohrer, Gerber, and Weibel regarded $CaIrSn_4$ as a good candidate for testing the STM at moderate vacuum ($\approx 10^{-6}$ Torr). Indeed, they published an STM image of a surface of $CaIrSn_4$ obtained at room temperature without further surface treatment; the authors presented line scans of $CaIrSn_4$ and remarked that for better visualization of the topography of the surface of $CaIrSn_4$ 'some additional lines have been interpolated (broken) between the smoothed scans'. Subsequently, Binnig and Rohrer referred to 'a new, improved tunnel unit with considerably increased stability'. They added that the improved unit yielded gold (Au) topographies.[72] It is most probable that this 'improved tunnel unit' is the 'second generation' STM.

Once this new technology was operational, Binnig and Rohrer could jump, so to speak, two steps ahead, and finally built the intended STM. They called the new (second generation) instrument, STM—the same name which they had used in the patents of 1978 and 1980. They could now discard the nomenclature of tunnelling physics and switch back to the same microscopy terminology which they had applied in the original patent disclosures. They could now speak as microscopists do—the path to success, the third phase, was established.

We have argued that Binnig and Rohrer worked within the framework of a detailed blueprint, but the technical papers do not divulge this fact. The researchers concealed the idea of the STM while trying to make it work. The terminology reflects this intention: 'improved tunnel unit', 'controlled tunnel unit', and so on. Binnig and Rohrer mixed aspects of the duel functions of the machine and the reader cannot discern which is which. In 1986, they tell the history of their instrument using the notion of 'generation', thus introducing order into the historical data. By doing so, they explicitly recognize switches in the history of the STM, switches which were concealed deep in the blur of the fuzzy rhetoric of the technical papers.

In their Nobel lecture, Binnig and Rohrer remarked that they had been too ambitious; it was only seven years after the project had begun that the principal

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[70] Note 63, 221.

[71] Note 32.

[72] Note 32, 58–59; cf. note 35.

problems of low-temperature and UHV instrument were solved.[73] Thus, on the one hand, the two patent disclosures determined the epistemological setting, namely, the blueprint, of a revolutionary microscope and, on the other hand, the realization of this knowledge, that is, the building of the instrument, was materially constrained by the state of the technology of insulating levitation systems in the late 1970s and early 1980s. This limitation forced the inventors to go a step backward, but their ingenuity made them jump two steps forward when they successfully replaced the ineffective isolation system. They could then continue with the execution of the blueprint of their original design for a STM. This story is undoubtedly dynamical; it begins with an ingenious theoretical framework whose realization required no less ingenuity in actual experimental practice.

Moreover, there is a sting to the story: the patent disclosures and the subsequent technical publications reveal that the original idea was an unintended invention. An effort at finding an 'appropriate tool' for studying inhomogeneities led Binnig and Rohrer to a new microscope. We have characterized this surprising development as the first switch; it was akin to a Gestalt switch. Rohrer reported on the initial motivation:

> We did not intend to invent a new microscope, we wanted to contribute to a better understanding of nano scale inhomogeneities, in particular those occurring in tunneling (an issue of our colleagues in the technology department working on the Josephson computer).[74]

Binnig and Rohrer filed a patent in which they defined a dual machine: spectroscope and microscope in one and the same device based on a tunnelling unit. In the patent disclosures, they call this instrument, STM. The date is important: they christened their new machine, 'STM', already at the end of 1978.

In the fall of 2004, in an interview with the journal, *Deutschland*, on the theme of creativity, Binnig remarked that 'the scanning tunneling microscope was developed ... without us intending to invent it'.[75] Binnig is then asked: 'So you owe the Nobel Prize to chance?' And Binnig replies, 'in a certain sense, yes'. To paraphrase John Milton (1671), Binnig and Rohrer were seeking asses, and found a kingdom. Chance may have played a role in this successful story, but it takes a great measure of ingenuity to see in the abstract (the design) what could be accomplished in the concrete (the instrument).

We have proposed at the outset the framework of 'generating experimental knowledge' as a suitable way for capturing the dynamics of the story of the STM. 'Generating experimental knowledge' addresses comprehensively the many facets of such story. Experimentation as a means of generating knowledge can proceed only if it constrains matter in a controlled fashion; but at the same time, it can succeed only if it leaves the system sufficiently free to allow for new phenomena to emerge. This tension between constraints and degrees of freedom constitutes the defining feature of our approach. The invention and construction of the STM exhibit well the three parameters of 'generating experimental knowledge', namely, the dynamic of

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[73] Note 4, 618.

[74] Note 20.

[75] 'The Creative Process', an interview with Gerd Binnig, *Deutschland* Forum on Politics, Culture and Business, No. 5 (October/November 2004), 46–47 (47).

correction and improvement, guided by conceptual reorientation, which drives the evolution of experimental system.

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