Visualizing the invisible nanoworld: ICT-enhanced reflection of imaging and images of atoms in nanoscience

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New tools for visualizing and manipulating systems down to the level of individual atoms play a decisive role in the advancement of nanoscience and assign a prominent role to images as a means of communication. However, making nanoworld imagery tangible to students or to the public is a challenge, because photo-realistic views interfere with adequate conceptual interpretations. The article focuses on scanning tunneling microscopy (STM). In order to develop a critical epistemology towards STM images, an acoustic analogy is presented using sound waves as probes to map arrays of acoustical resonators. Starting from hands-on experiments, ICT-tools are used to create an augmented reality that transforms sound fields into visual representations. The acoustic near field imaging is fully transparent and classical-quantum analogies establish a correspondence with tunneling spectroscopy. A thorough reflection of the imaging process helps to counteract naive misinterpretations of nano-visualizations. Moreover, the acoustic model stimulates new insights by elucidating the power of near field scanning microscopy to resolve structures much smaller than the wavelength.

Keywords visualization; ICT-enhanced hands on experiments; nanoscience education

1. Tangible atoms: tools for imaging and exploring the nanoworld

Contrary to textbook wisdom, scientific advancement is more often driven by the development of new tools than by the development of new scientific concepts [1]. The recent progress of nanoscience demonstrates the role of instrumental devices as facilitators and catalysts for new insights. It reveals the close interweaving between the technical function of tools and their epistemic role in promoting the conceptual development of the field. The invention of scanning tunneling microscopy (STM) thirty years ago opened up a visual window to the nanoworld. Scanning an atom sized probe tip across surfaces, measuring the tunnel current, and transforming the sequential signals from each scan into a computer generated picture created amazing views of system with atomic resolution [2]. The method sparked off the conception of a whole series of different scanning microscopy instruments [3]. Various probing schemes allow researchers to explore, to visualize and, to some extent, to manipulate matter down to the level of individual atoms or molecules. These new tools provide fascinating views into the fabric of nature both in the inanimate and in the living realm. They initiated the rapid development of nanoscience as a scientific field where the classical domains like physics, chemistry and biology converge and meet at the atomic or molecular level. Nanoscience already impacts on many areas including material science, information technology and the life sciences. Emergent technologies in these key areas profoundly affect our lives and the workplace. Therefore, scientific literacy, including a basic knowledge of nanoscience concepts, is highly relevant for a better understanding of our everyday world and for judging ongoing and future technological developments.

Images of the invisible nanoworld play a special role as a means of communication in the research community, in public discourses and, to an increasing extent, in teaching. Thus, an essential component of nano-literacy comprises a sufficient understanding of the messages encoded in pictorial presentations. Although, with the advent of STM, atoms could be rendered "visual", an interpretation of their computer generated representations is far from trivial. An intuitive access is impeded by the wide gap between classical macroscopic models of matter and the strange behavior of systems on the nanoscale, where counter-intuitive quantum, thermal and size effects prevail. In addition to that, the mapping process differs fundamentally from conventional optical imaging and magnification techniques. Nanoworld visualizations have stimulated concerns about the veracity of images and their role of presenting and representing. Critical discussions about the issues of visualization that arise in scanning probe microscopy often combine views from philosophy of science with perspectives from art [4-6]. What is actually shown in the images of atoms created from STM scans? To what extent do these new tools for visualizing invisible entities transform our epistemology of seeing, touching, and knowing? Do they enhance and enrich our perception system, or do they break with the habits of traditional imagery and visual thinking.

The present article complements these theoretical reflections with a practical hands-on approach that conveys model based knowledge on how to visualize the invisible. In order to make the imaging process tangible, a macroscopic analog of the STM method is investigated. It uses near field acoustic scanning and computer visualization to create a visual representation of the resulting sound field. The processes that transform the acoustic signals to a different sensory modality are fully transparent and visualizations of acoustic structures are highly similar to STM imaging. By restricting theoretical considerations on quantum theory and on the wave nature of matter to a minimum, the present experience-based approach has a good chance to convey basic ideas about nano-imagery to a lay audience.
2. Images, imaginations and models: decoding the icons of nanoscience

The interpretation of the fascinating images from individual atoms obtained by STM demonstrates the clash between our intuitive, classical views of macroscopic matter and the behavior of systems at the nanoscale. For millennia, the notion of atoms had been a matter of passionate philosophical debates. Only a century ago, the reality of discrete material corpuscles was accepted via indirect evidence and sophisticated theoretical arguments. Although, finally, their existence was out of question, atoms remained elusive theoretical entities. Nobody was actually able to see and to experiment with single atoms. Only special high resolution electron microscopes could render atoms visible [7]. Now, with the advent of STM, images of atoms can be created with desktop machinery. Atoms are no longer mere things of thought. They can be addressed individually as "tangible" quasi-classical entities. Under favorable conditions, they can be moved across surfaces and brought to defined positions. This opens up new ways of engineering atomic scale structures from the bottom up.

Some STM-images have become famous for delivering a proof of principle to build up nanoscale systems atom by atom. Fig. 1a shows the first nano-sized logo created by positioning xenon atoms on a nickel surface. This event was later acclaimed as "35 atoms that changed the nanoworld" [8]. Fig. 1b shows another famous prototype of a man-made nanosystem, the "quantum corral". A circular structure is created by moving 48 iron atoms on a copper surface. The structure acts as a reflecting barrier that scatters surface electrons back into the circular confinement giving rise to a pattern of standing waves reminiscent of water waves in a circular pot or a frying pan.

These images acquired an iconic status as demonstrators for reaching an ultimate engineering frontier. They made their way into popular magazines and textbooks all over the world. They show the positions and even the shapes of atoms. Their visual appearance in a three-dimensional landscape is augmented by adding colors and shades. But what views of reality are actually conveyed to a person not acquainted with the imaging method and with the subtleties of quantum mechanical models of matter? What aspects of reality do these images present, what is an instrumental artifact and what is imagination? Apart from methodological considerations, a critical reflection how to convey the message of nanoimages to the public has to take findings from science education research into account.

Many reports document that students are faced with considerable problems when they use particle models to explain the behavior of matter (cf. [10-12]). Students inappropriately transfer macroscopic characteristics from the everyday world to the atomic models. For instance, they uncritically assign macro-attributes such as colour, form, elasticity, or temperature to atoms. In the bottom up direction, an explanation of the emergence of new macroscopic properties from combining atomic entities is extremely demanding. Students tend to confound the borderline between model and reality. Frequently, the same level of reality is attributed to models of atoms and to everyday objects like tiny billiard balls or marbles. Moreover, students have problems in distinguishing between different models and in acknowledging their hypothetical and limited character which is tailored to explain specific features of observations.

The fascinating visualizations of nanosystems do not eliminate these well documented and deeply rooted conceptual problems. On the contrary: the photo-realistic presentation of atoms favors and even reinforces naïve realistic misinterpretations of atoms as scaled down portions of a continuous macroscopic material stuff. The visual message conveyed by the three letter logo is enhanced by the special graphical rendering of the atomic signatures. Atoms are given the appearance of tiny heaps of matter that sit on a plane surface. They appear to create corrugations in the surface topography comparable to dots in Braille letters. This affords a purely classical view of mapping a sharply defined surface topography similar to a relief map of an atomic landscape. However, such a mechanic view of the imaging process is inadequate; e.g. it does not explain why only the xenon atoms are visible while the atoms of the nickel substrate are hidden.
The corral image presents a more complex quantum landscape that includes a presentation of the wave-like nature of electrons. Again, it shows atoms as localized entities. They seem to stand out from an extended "sea" of wavelike corrugations which superpose to a circular pattern inside the ring of atoms. This pattern does not result from any real topographic corrugation but indicates the behavior of quantum particles in a box. It maps the probability density distribution of surface electrons inside the atomic fence. Within the circular confinement different standing wave patterns of the electronic wave function can exist. They depend on the energy of the electrons in analogy to vibration patterns of circular drumskins that depend on frequency.

This qualitative discussion suffices to clarify that STM-images are not photo-realistic pictures of a scene. An adequate interpretation has to take the deep conceptual gap between the classical and the quantum realm into account. Factualy, the images can be regarded as quantum theory condensed to a pictorial representation. If we want to convey the inherent message in classical, macroscopic terms we cannot evade using a strange hybrid language. It combines complementary models of the perceived structures and condenses them into a single image:

- Quasi-classical perspective (describing atoms as localized particle-like entities)
- Quantum perspective (standing wave patterns as indications of the wave-like quality of electrons).

It depends on the experimental settings which perspective prevails. With insufficient theoretical knowledge it is impossible to reconcile apparently conflicting views and to create a coherent representation. A clash with our intuitive conception of matter is inevitable. Fig. 2 visualizes the clash and the tension created by incompatible views, indicated by tree conflicting models of atoms in the observer's head. Students tend to discuss nanoscale phenomena using the simple billiard ball model of an atom or Bohr's planetary orbit model. Neither model can account for an adequate interpretation of the structures. Only full quantum mechanical models will do, indicated by the standing wave patterns of electronic orbits.

Fig. 2 The clash of models: incompatible models of atoms can interfere with an adequate interpretation of nanoscale images.

The wave nature of matter at the nanoscale affords astonishing effects that might become technologically relevant in the future. Fig. 2 shows another icon of nanoscience, the quantum mirage [13]. An elliptical array of 36 cobalt atoms acts as an electronic mirror creating the quantum mirage of an atom. The magnetic properties of a cobalt atom in the right focus of the ellipse are mapped to the empty left focus, indicated by the purple color [14]. This system demonstrates the feasibility of transmitting the electronic signatures of a magnetic atom over a distance, and to create magnetism detached from an atom. Thus the quantum mirage phenomenon shows quantum magic in action and adds a further component to the tension of what is real and virtual on the nanoscale. The image transports a message: What still appears as virtual today could turn real in future technologies.

The inherent multi-perspectivity makes nano-science images comparable to works of art, especially to works of cubistic painters who sought to condense different perspectives of a scene into a single image [5]. Yet, different from many paintings and other works of art, nano-images do not speak by themselves to an inexperienced spectator. We have to look for adequate methods of scaffolding and conceptual transformations that convey the strange quantum magic to a wider audience. A metaphor from the early days of quantum physics can be used for that purpose. It provides an intuitive access to aspects of a nonclassical world without getting too deeply involved with the subtleties of quantum theory. This metaphor also paves the way for an experience based approach to STM and other types of scanning probe microscopy in nanoscience.
3. Extending perception: Bohr's walking stick metaphor of knowledge acquisition

In order to promote a qualitative understanding of the challenges and the limitations of nano-visualizations it is helpful to recur to philosophical discussions from the early days of quantum physics, when physicists were deeply troubled by the apparent clash between the world view of classical physics and the new theory of quantum phenomena. One of the founders of quantum physics, Niels Bohr, created an appealing metaphor to facilitate a better comprehension of the new situation that raises deep doubts on the received classical views such as the conception of a detached observer who collects complete knowledge about the state of the external world. How can one come to terms with the strange nature of the quantum world? Bohr compares the epistemological position of a classical observer inspecting the invisible quantum world to a person using a walking stick to find the way in a dark room [15]. At first sight, the stick is a mere tool to extend one's reach. The device can be integrated into the observer's cognitive system in different ways giving rise to different views of reality.

The knowledge we gain depends on the questions we pose. It depends on our grip of the cane where to place the dividing line between subject and object. If we grasp the cane firmly, it extends our reach and the demarcation line with the external world is shifted to its end. If we hold it loosely, the cane is the object that we feel. It is allowed to couple dynamically to external objects and we can sense the cane's motion. In the firm grip mode it is possible to determine the position of objects exactly while momentum measurements require the loose grip mode. Contrary to classical physics, a simultaneous measurement of complementary variables like position and momentum is impossible in the quantum domain. Thus, the walking stick metaphor depicts various issues of intervening with and gaining classical knowledge about the quantum world. It demonstrates the arbitrariness of the cut between subject and object. Moreover, it is a classical illustration of the complementarity between the measurement of position (firm grip) and momentum (loose grip). Ultimately, it stands for the freedom of choice of selecting which mutually exclusive properties to observe or to measure in an experimental setup.

The struggle with the strange nature of quantum reality carries on to the present. It also touches upon the question how to develop a critical epistemology towards visualizations in nanoscience. Bohr’s blind-man-walking-stick-model anticipates modern scanning probe microscopy methods in a visionary philosophical way (fig. 3). It also facilitates a qualitative understanding of the epistemological problems inherent in the visualization processes. STM is a method that combines principles of classical electronic-mechanical engineering with quantum physics. The classical part refers to scanning surfaces at atomic distances with a tip-shaped probe that ends in a single atom. A piezoelectric mechanism drives the scanning motion across the surface and provides an adjustment of the vertical distance with subatomic precision. Quantum physics comes in by measuring the tunnel current after applying a voltage between tip and surface. The current is a product of the wave-like properties of electrons that allow electron "clouds" to extend into regions that are forbidden classically. Therefore, tunneling occurs before a full mechanical contact is established. The tunneling process takes place between occupied and empty electronic orbits of the approaching tip and surface atoms. The current strength depends on the overlap of the orbits and increases exponentially by decreasing the distance between tip and surface. STM images are presentations of the dependence of tunnel current on the position of the probe, and there are many ways of visualizing this information.

In STM, the experimenter's choice comes in by selecting the mode of operation and by adjusting relevant parameters such as voltage, tunneling current and distance. Basically, there are two different modes of measuring: the topography and the spectroscopy mode. In the topography mode, the tip is scanned across the surface at a constant tunneling...
current. This is achieved by adjusting the distance between tip and surface through a feedback mechanism. The tip motion can follow the apparent surface topography closely, because the tunneling current is highly sensitive to the distance. The first STM-images that presented the structures of silicon surfaces in real space were created by using this mode [16]. In the spectroscopy mode, the dependence of tunneling current on the applied voltage provides information about the density of electronic states involved in the tunneling process. The local density of states available for the tunneling electrons is measured by the differential current $\Delta I/\Delta V$ [17]. This is achieved by superposing small modulations $\Delta V$ on the tunneling voltage $V$ and detecting the resulting current amplitudes $\Delta I$ while the distance between probe and surface is held constant during the scan.

The observer has the freedom to choose which aspects of the structures under investigation are actually measured by selecting an appropriate operation mode. The topographic mode highlights corrugations and relates them to surface topography. They are presented like real material topographic structures but, actually, they reflect corrugations in the density of electronic states. In a visual parlance, the images do not reflect any "hard" outer atomic shell; they depict the effects of the electron clouds which possess softly decaying borders due to their wave character. This puts restrictions on an interpretation of the atomic corrugations as purely topographic features. The spectroscopy mode probes into the electronic structure of the surface atoms in a more detailed way. It investigates the overlap of electronic states between tip and surface at specific energies.

As these details are highly technical, one might arrive at the conclusion that deeper insights into the imaging processes are incommunicable to non-experts. However, such a conclusion is premature and neglects the potential of learning and understanding by analogy. The STM-spectroscopy mode transfers easily to an analogous situation from the macroscopic world and to a sensory modality that we use intuitively. In classical language, the matching of energies and the overlap of electronic probability distributions of probe and surface states corresponds to a resonance. This resonance analogy underlies the classical scanning method which is described in the following chapter.

4. Auralizing atoms: an acoustic STM model

Many teaching models for scanning probe microscopy have been proposed. They demonstrate the operation principles by scanning macroscopic surfaces through direct mechanical contact or magnetic forces [18-20]. In some demonstrations the atoms are modeled by marbles or table tennis balls. These mechanical models elucidate only the classical part of scanning and support mechanistic misconceptions. They do not counteract the naive material stuff view of static atomic structures or the rigid shell assumption of atomic surfaces that was criticized above. The essential component of quantum mechanical interaction between electronic states is missing. In STM, the wave-like character allows electrons to bridge the tunneling gap and to probe into the structure and dynamics of electronic systems. This quantum mechanical effect, which appears highly strange at first sight, is not restricted to matter waves. It can be simulated with classical waves and even sound waves will do the job!

We know from our own acoustic experience that it is possible to locate sound sources by the wave patterns they emit. We even do acoustic spectroscopy intuitively in order to recognize the characteristic spectrum of a voice or the timbre of musical instruments. Detecting, interpreting and locating acoustic events by inspecting patterns of resonances are common accomplishments in auditory perception. Thus, the basic sensing principles of STM to locate objects and to investigate the inherent dynamical structures by doing spectroscopy are not new to our perception system. However, auditory perception is hard wired to carry out these analyses unconsciously. We have to make our implicit acoustic signal processing strategies explicit in order to appreciate their potential for creating an acoustic simile of STM imaging.

One can start with a hands-on approach and use an acoustic probe to investigate acoustic resonators such as open bottles or cans. The probe is constructed easily by extending an earphone capsule with a rubber hose (length 3.5 cm). The earphone is connected to a sound generator and the probe is placed next to the resonator's opening. If the sound frequency meets the resonant frequency of the acoustic system, an increase of loudness is heard. In this way it is easy to detect the presence of a resonating object aurally. Once their frequency is known, objects can be localized by frequency meets the resonant frequency of the acoustic system, an increase of loudness is heard. In this way it is easy to detect the resonating object aurally. Once their frequency is known, objects can be localized by frequency.
Fig. 4 Sketch of the acoustic scanning macroscope. The two-dimensional matrix of the sound field data is transformed into different visual representations: (a) contour plot, (b) mesh plot, (c) three-dimensional graphical rendering.

The system creates mappings and visualizations of acoustic structures. For obvious reasons it can be dubbed a scanning acoustic macroscope. The imaging process is obvious. Fig. 4 presents schematically the collection of sound field data from a sequential scan point by point and line by line. The two-dimensional data array is transformed into different styles of visual presentations. Conventional programs such as Excel or SigmaPlot can be used for that purpose. Their graphical style galleries include three dimensional renderings that create impressive spatial views of the structures.

Fig. 5a shows an actual measurement of an array of resonators made up from yoghurt bottles. The sound frequency of the acoustic probe is tuned to detect the lowest bottle resonance. Different from nanoworld systems, it is possible to present a photo showing the real structure for comparison. The acoustical mapping presents a landscape completely different from the optical image. It maps the positions of the bottles, but it is impossible to make any statements about their real shape. This feature is hidden acoustically. The acoustic scan shows a maximum in the middle of the resonator’s opening where no material structures exist. The coupling with the bottle’s resonance is optimal at this position. Fig. 5b demonstrates the role of resonances in creating an acoustic image that is sensitive to the type of resonators. The picture at the left shows a scan of a regular hexagonal array of identical yoghurt bottles. The picture on the upper right presents an apparent vacancy in the same arrangement. However, this is not a real vacancy created by taking one bottle out of the array. The bottle is still there, but its acoustic properties were changed by partly filling it with water. This modified bottle is invisible, because it is not in tune with the probing frequency. One must be aware of misinterpretations resulting from the resonant probing scheme. The naive interpretation of the missing hump as a vacancy is incorrect; instead, the missing structure indicates a different species of bottle, simulating an atomic defect. It can only be detected by matching the probe frequency. Thus, the acoustic method is not only able to locate the objects. Its spectroscopic features allow detecting the specific species of the acoustic "atoms" depending on the spectra of their internal degrees of freedom.

Fig. 5 Acoustic near field imaging of an array of yoghurt bottles (a). Acoustic imaging of a two-dimensional "crystal" of bottles. The upper right scan shows an apparent defect created by a bottle partly filled with water (b).
The scanning acoustic macroscope simulates STM-imaging to an amazing degree of agreement. The images create visual impressions and associations that are not different from the presentations of the atomic structures discussed in chapter 2. An unbiased observer cannot tell if a nano- or macro-system is presented in the pictures. As the acoustic imaging method is completely transparent, a thorough reflection of the mapping and transformation procedures contributes to developing a critical epistemology towards pictorial representations of atoms. The acoustic image of resonating structures in comparison to their photos (fig. 5a) makes the restrictions to naïve realism tangible. The acoustic scan represents only certain aspects of a more complex dynamical reality. The humps and corrugations do not contribute to developing a critical epistemology towards pictorial representations of atoms. The acoustic image of imaging method is completely transparent, a thorough reflection of the mapping and transformation procedures chapter 2. An unbiased observer cannot tell if a nano- or a macro-system is presented in the pictures. As the acoustic visual impressions and associations that are not different from the presentations of the atomic structures discussed in visualizations have more in common with acoustic imagery than with optical images. Instead of seeing atoms, it is more adequate to speak of hearing them and to think of tuning into their internal dynamics. Formally, the partial analogy of sound-waves with matter waves is based on the isomorphism between the Schrödinger-equation in wave mechanics and the Helmholtz equation in acoustics. The isomorphism of various wave representations is at the heart of many classical-quantum analogies [21]. The degree of similarity between acoustic waves and matter waves depends on the boundary conditions of specific systems. In the present context of probing the local acoustic impedance there is a correspondence with the impedance of electron waves in tunneling spectroscopy. The local density of states available to electrons in tunneling is measured by the differential STM current ($\Delta I/\Delta V$). This is equivalent to an impedance measurement of electron waves [22]. In this analogy, the acoustic power corresponds to the flux of tunneling electrons which depends on tunneling probability. The acoustic power is proportional the square amplitude of sound pressure while the quantum mechanical probability of detecting a particle is proportional the square amplitude of the wave function.

5. Visions beyond limits: tools to empower imagery and creative imagination

The local probing scheme implemented in the acoustic macroscope can be considered an acoustic version of Bohr's walking stick, enhanced by ICT to create an image of the acoustic properties in close vicinity to the tip of probe. Depending on the local impedance, the probe tip transmits sound power via resonating structures to the acoustic far field. This scheme of near field imaging reveals a remarkable property compared to optical magnification techniques. Sound waves with a wavelength $\lambda \approx 13$ cm (2.6 kHz) are used to map structures with much smaller extensions in the centimeter range. In conventional optical magnification by lens systems such a resolving power is not possible. The operation of an optical microscope is restricted by the diffraction limit, given by the Abbé-criterion [23]. The minimum distance $\Delta x$ between two point sources that can be clearly separated depends on the wavelength $\lambda$ and the numerical aperture NA of the instrument: $\Delta x = 0.61 \lambda / NA$. This restricts the resolution limit of conventional optical microscopy to the order of $\Delta x \approx \lambda / 2$. Near field imaging overcomes these restrictions and allows the detection of structures much smaller than the wavelength.

Although the principles of optical near field imaging had been in existence for more than half a century, it required the spark from STM that initiated the further development of powerful optical techniques to beat the Abbé-diffraction limit. At present, many novel schemes for optical nanoscopy are being devised; e.g. the STED method (stimulated emission depletion) uses point-like optical excitations in fluorescent molecules and optical microscopy to create images far below the optical resolution limit [24]. These new tools of optical super resolution microscopy provide detailed views of the molecular machinery in living cells and open up fascinating new ways to explore life at the nanoscale.

In the context of innovation and conceptual transformations driven by tools it is interesting to note the change of perspective that the present acoustic macroscope demonstration initiates. Originally conceived to convey the principles of STM, the acoustic scanning method inspires insights into more distant fields such as super resolution microscopy. The experiment literally develops a life of its own; it illuminates beyond its original purpose and stimulates new insights. These creative transfer processes require abstractions and the linking with other domains. Thus, the technical tool can unfold the surplus meaning that it carries. It transforms into an epistemic device that assists in creating new knowledge. Similarly, on a much wider scale, the recent advances of nanoscience and nanotechnology demonstrate the close interweaving between the technical function of tools and their epistemic role in promoting conceptual advancement of the field. The obvious success of visualization in nanoscience underlines the productive role of imagery and procedural knowledge that drives creative imagination. However, classical imagery needs adequate conceptual adjustment to meet the requirements of the nano-domain where many received models from our everyday world break down.
As a complement to theoretical knowledge, the present approach focuses on fostering model based knowledge and on learning by analogies in order to make nanoscience imagery accessible and productive for a wider audience. Although STM images do not support immediate insight and require a conscious reflection, they do not break with the habits of ordinary perception. In the strange domain of transition between classical and quantum behavior at the nanoscale, the essence of imaging by using wavelike qualities is much better represented by a transformation to hearing. The present ICT-enhanced cross modality mapping works in both directions. It visualizes acoustic fields and auralizes images. The critical reflection of the inherent transformation processes clarifies some puzzles of creating and interpreting pictorial representations of atoms by analogy. This transformation might seem unusual at first. Nevertheless, it is fully transparent and gives an intuitive impression of what is presented. It conveys basic ideas of imaging by scanning probe microscopy to students or to a lay audience in a qualitative, model-based and analogic way without going into details of quantum theory.

Nanoscience imagery is accessible in a semi-classical correspondence. Without such correspondences, insight in quantum behavior is strongly impeded, because it is unlikely to develop an adequate imagery. Classical-quantum analogies afford the generation of dynamical mental models. Their execution allows anticipating behavior and making predictions. Unfolding model based knowledge and bringing life to abstract and complex principles is crucial for the advancement of nanotechnology. We have to utilize similarities and analogies in a productive way and to explore their potentials as well as their limitations, in order to understand and to exploit the creative powers of the nanoworld. It is both fascinating and challenging to observe and to contribute to the ongoing growth of knowledge facilitated by modern nano-versions of Bohr's walking stick.

Acknowledgements This work was supported by Deutsche Forschungsgemeinschaft as part of the public outreach project of DFG SFB 677. Technical assistance by Martin Lass, Klaus Boguschewski and Dorothea Stich-Bohrnsen is gratefully acknowledged.

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