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Empowering Experiments as Epistemic Engines: Hands-on Models and Analogies in Nanoscience Education

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Abstract

Experiments play many different roles in research and education. While in the traditional view experiments are considered mere test instances of models and theories they can unfold a creative life of their own beyond that formal role and foster fluid knowledge. Based upon arguments from epistemology of science as well as educational and cognitive theories, the present contribution highlights their generative functions in stimulating productive thinking, knowledge transfer and theoretical reflections. The article substantiates the view of experiments as engines of intuition and knowing by providing introductory examples from nanoscience education based on hands-on models of scanning probe methods. In combination with analogical reasoning the models convey an experience based access to a highly productive interdisciplinary field of research and innovative applications. Apart from visualizing the invisible and making transformations of forms and functions tangible, the toy systems embody basic principles that open up intriguing views upon the universality of emergent processes in the physical and biological realm.

Keywords: Analogies; Experiments; Inquiry Based Learning, Nanoscience; Toy-Models

Reshaping Science Education: The Challenge of Fostering Active Learning and Creative Minds

The rapid increase of knowledge in a wide range of disciplines triggers scientific and technological developments that deeply affect our lives and transform our culture. Science education is challenged to keep pace with the rapid and still accelerating evolution. In the recent past we could witness an increasing political interest in science education resulting in a plethora of programs to improve the quality science learning and initiatives to raise interest in mathematics and science subjects. Universities and research institutes all over the world run outreach activities to enhance science communication and to encourage young people to take up a career in science and technology related fields. Concerns about competitiveness are a main driving force towards educational reforms in view of the imminent lack of scientists and scientifically literate workforce, which could severely restrict the innovative potentials of a society. Beyond economical factors ecological and sustainability issues count as well. Science and science based evidence can be considered central to understanding and addressing the most important societal and global challenges that we encounter. Moreover, in the tradition of enlightenment, there is the hope that science will help in providing a rational counterpoint to the irrationalism that we face these days.

Although the various science education initiatives differ in scope and subjects, they largely agree on a general methodological level by giving the process of science inquiry a central role. For many proponents, inquiry based science education is considered a universal tool to promote active learning and to counteract the deficiencies of traditional knowledge transmission models of teaching, such as superficial learning and declining interest in science subjects. However, meta-analyses considering the impact of inquiry based science instruction on K–12 student outcomes do not come up with overwhelmingly positive results. There are moderate effects with respect to active thinking and to drawing conclusions from evidence [1]. The empirical findings are by far less conclusive when it comes to the core issue to what extent inquiry based learning can foster conceptual understanding of the "hard" sciences. Moreover, on the practical side, research about implementing inquiry based instruction in mathematics and the individual science domains shows reservations of many teachers to pure inquiry depending on the teaching traditions, the subject areas, and on school system immanent restrictions [2]. More efforts are necessary to design inquiry and experience based learning to match the requirements of efficient science education. Learning how science works must be adequately balanced with conceptual learning.

Along this direction, the article presents exemplary approaches to nanoscience teaching that combine the needs for improving conceptual understanding with the benefits of hands-on inquiry and experience-based learning. The focus on the field of nanoscience is obvious in view of the educational requirements to support young people in understanding scientific concepts and reasoning. This cross-cutting area of science and technology emerged in the past decades, largely triggered by new methods to visualize and to interact with systems on the atomic scale. Beyond the traditional disciplinary demarcations of physics, chemistry biology and engineering, new fields of research and development are created that exploit the atomic, molecular and collective properties of nanoscale systems. Emerging technologies will deeply impact on our society and transform many areas of science and engineering, including material and life sciences as well as information and communication systems.

Educational approaches to nanoscience are demanding due to various reasons [3]. As concepts and methods from different domains come together domain specific knowledge is decisive. Beyond that, a comprehensive view requires transcending the traditional disciplinary horizons. With respect to acquainting school students with the basic ideas of the subject, the abstract, intangible and counterintuitive features of the nanoworld come to the foreground. Depending on scale new properties emerge which defy an easy explanation in terms of everyday experience. Finally, on the bottom level, the behavior of nanosystems is dominated by quantum effects. The inescapable strangeness of the underlying quantum world sets high hurdles to efforts of educational reconstruction and design. The present contribution advocates an approach that implements inquiry and experience based elements, suited for introductory teaching. However, due to the inherent complexity and abstractness of the subject, the teaching strategy critically depends on thoughtful guidance providing a balance between bottom up and top down processes such as open explorative inquiry and guided abstractive reflection and generalization. The article presents a comprehensive overview of different examples of hands-on nanoscience models starting from outlining guiding ideas from educational and cognitive theories and arguments from the epistemology of science.

The Inquiry Cycle: Rationalizing the Creative Interplay of Complementary Modes of Knowing

We frame our approach within a generative model that applies to inquiry processes in science as well as to design processes in technical disciplines. It highlights the productive role of experiments and analogical reasoning for creating and unfolding fluid knowledge. Procedural knowledge gained from and embodied in experimental actions represents a necessary complement of theoretical knowledge. This contrasts to the traditional account of scientific methodology that considers experiments mere test instances to confirm or refute models and theories. In accordance with the received notion the role experiments in teaching and in textbooks is mostly reduced to introducing, justifying or verifying theoretical ideas. However, the epistemological role of experiments is by far more diverse and productive [4,5]. On par with theory, experimentation does have a life of its own in the development of science [6]. The notion of key experiments accentuates their role as icons of knowing that initiated new theoretical thinking. In favorable instances, theoretical ideas can be condensed into and emerge from a single "beautiful" experiment [7]. Along these lines the present contribution elaborates the creative life of experiments in teaching and learning. It highlights their role as epistemic engines that assist reasoning and solving novel problems in science, an aspect largely ignored in mainstream educational theories [8].

There are many ideas on the nature of scientific inquiry and design. Most conceptions agree upon their cyclic character that iteratively link two different worlds, the world of experience and the world of ideas and theories (Figure 1). Creative processes, which cannot be described in a fully logic or algorithmic language, play an important role at the interface between theory and practice or idea and experience. These creative leaps at the interface work in both directions: bottom up from experience to theory and, top down, linking ideas with the real world. In research this somewhat idealized view corresponds to the iterative cycle of modeling and experimenting that starts from wondering, asking questions and identifying ways how to create predictions and solutions to a problem on the basis of suitable models and theories. The corresponding processes in the technological design cycle refer to the development and evaluation of ideas, based on suitable assumptions, models and theories, and to construction, testing, trouble shooting, and optimization.

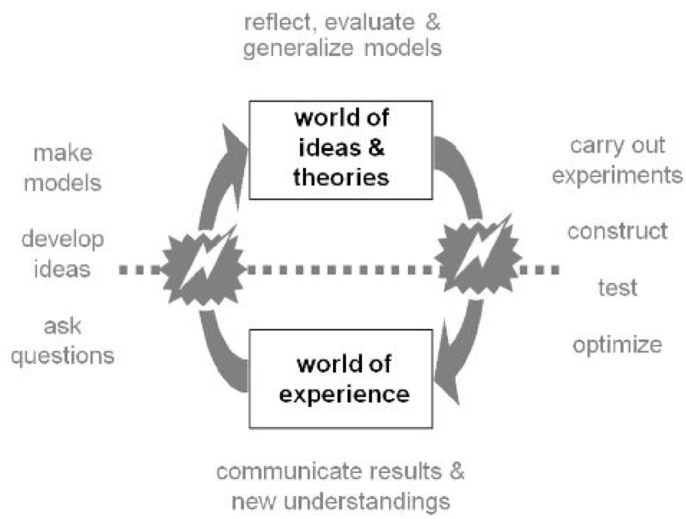

Figure 1: Cyclic model of inquiry and design in science and engineering.

In physics, the model is compatible with the views brought up by prominent researchers, for instance with Einstein's EJASE model of scientific theory construction, where the 'J' addresses the creative jumps between experience and theory [9]. The modeling cycle requires a clear distinction between the two worlds separated by an epistemic cut. In spite of the non-deductive 'creative' elements at this interface, the complete process described by the cyclic interweaving and reflection of generative and evaluative components is rational. Figure 1 focuses on the level of individual processes. The social components of knowledge co-construction are omitted for clarity. Many pedagogical models have been put forward, which are modified versions of this basic cycle [10]. With due adaptations, they also provide the core of various educational frameworks of inquiry based learning.

The generative model of the inquiry/design cycle conforms to the demands of educational constructivism that identified favorable conditions for knowledge construction and conceptual change. However, transforming constructivist ideas about learning to efficient constructivist teaching is anything but trivial [11]. It appears a too naive assumption that learners are able to discover the relevant structure principles and big ideas of science by themselves or by interaction with their peers without suitable guidance by experts. Evidence from unguided learning clearly demonstrates the benefit of more strongly guided instructions [12]. In the views of these authors, the challenge to constructivist teaching is to unite the intuitively appealing view that learners must become active and construct their knowledge with the requirements of human cognitive architecture.

What is so special about science-related cognitive processes that our cognitive systems pose severe impediments to the learning of science in school? We focus on physics, because this domain is paradigmatic for many problems of learning and understanding science, especially with respect to the role of mathematics in creating and unfolding physical models and theories. Physics is rated "hard" by many learners mainly because of its abstractness and its mathematical rigor. A more refined analysis identifies different forms of knowing and their interplay that render the subject difficult and counterintuitive. Physics combines concrete and abstract approaches to create and refine models and theories of the world, which often are counterintuitive and highly different from the naïve views guided by experience from our everyday reality.

The underlying dichotomy between concrete and abstract approaches is generic to higher cognitive processes. Most models are dual and assume an interlinking of two different information processing strategies [13]:

- The logic-analytic system operates in a sequential way. It uses logical rules and algorithms to combine information and to arrive at conclusions. This declarative mode runs rather slowly, effortful und requires conscious control.
- The experiential system operates in a largely associative, experience- and model-based analogical way. This procedural mode runs fast, effortless and automatic, largely inaccessible to conscious control.

This dichotomy persists in the epistemology of science. The emphasis on declarative knowledge corresponds to the nomologic-deductive view of science while the procedural focus is in line with the semantic, model based view [14]. The former stands for the formal rigor, difficulty and abstractness of the discipline while the procedural and analogical strand is based on models which can have a concrete content related to everyday experience, to intuition, easiness and tangibility.

The procedural knowledge is largely implicit, holistic and visual. It can be unfolded in intuitive ways circumventing explicit argumentation by chaining patterns of real or imagined actions; one action triggers the next. The easiness of mental simulations has a price: it is error prone. Due to inherent capacity restrictions it includes only fragmentary aspects of reality. The easy, intuitive model-based part of knowledge acquisition is largely in line with privileged learning. It applies to first language acquisition, to dealing with basic mathematical concepts such as numbers and simple geometric relations or to using physical primitives such as causality or the force-action schema. However, the easy, intuitive channel of model making is fallible as many examples demonstrate that involve intuitive physics arguments [15]. Although locally successful for dealing with everyday situations, it cannot be generalized and often leads to a wrong global picture. Relying on students' intuitive responses also severely restricts the potential of inquiry learning. In carrying out experiments students often only see what they already understand and much less reshape their knowledge in order to better understand what they see [16]. Observations are intentional acts that depend on prior knowledge. Learners tend to interpret the outcomes of experiments in terms of what they know or surmise instead of adapting or reorganizing their knowledge to match the experimental evidence.

As a complement and a corrective to the fast-intuitive procedural channel, the explicit but much slower analytic and rational mode is required in order to generalize experience and to condenses experience into rules, principles and laws that apply more generally. In the other direction the procedural mode is required as the empirical referent of the theoretical strand. Procedural knowledge is necessary to anchor concepts in experience and to unfold the consequences of theoretical models that can be tested empirically. Both modes of learning and knowing are interdependent. Teaching must be orchestrated in ways that conform to this interdependency and, moreover, it must include reflections to make it transparent and to the learners.

Teaching for Inquiry: Orchestrating the Reflective Interplay of Conceptual and Procedural Knowledge

From a cognitive perspective, many difficulties of coming to terms with the hard aspects of science can be traced back to the limitations of our working memory. This system stores and iteratively refreshes information on a short timescale, related to the immediate presence of our conscious thought processes. It requires extensive experience to devise and to handle complex scientific concepts in our cognitive systems which were optimized for quite different purposes. Starting from the magical number 7+2 as a first appealing estimate of its capacity limit [17], research has greatly elaborated the important role of working memories in education and learning [18]. Current models of working memory assume two modality specific storage systems apart from the central executive: the phonological loop and the visuospatial sketchpad [19]. In its essence, the dual model comprises an essentially sequential stream of processing, similar to the sequential chain of events in language and action. It is entangled with a parallel, more holistic mode, related to visual and spatial information processing. The dual character is largely in line with the above complementary modes of scientific reasoning that discriminate between holistic structural elements (the theoretical landscape) interlinked with procedural model-based elements of anchoring and unfolding the theory in experience.

The limitations of human information processing require the 'chunking' of concepts into smaller units of knowledge that can be handled, connected and transformed depending on the degree of experience. In scientific reasoning, a successful chunking of abstract concepts is largely theory based, because it has to include relevant characteristics of a phenomenon and leave aside irrelevant or superficial features. Thus, model making is an iterative process. It starts from an initial idea which is successively refined into schemas, patterns, rules, regularities, principles, axioms and laws that finally are condensed into a coherent theory. The inward bound part of chunking is based on condensation processes that associate different properties and combine them to a conceptual entity. In the opposite direction, relating the concepts to structures and processes in the real world requires some kind of unpacking or dynamical unfolding. This part is largely procedural, and experience based. Figure 2 schematically depicts the interweaving of knowledge condensation and unfolding. The chunking processes allow for iterative refinement and focusing of knowledge in accord with the inquiry cycle. Thus, the evolution of scientific concepts can lead to a nested structure of properties that pertain to different levels of conceptualization. Their unfolding is context and level dependent. While this hierarchy of nested concepts is a common notion to experts it poses severe obstacles to novice learners.

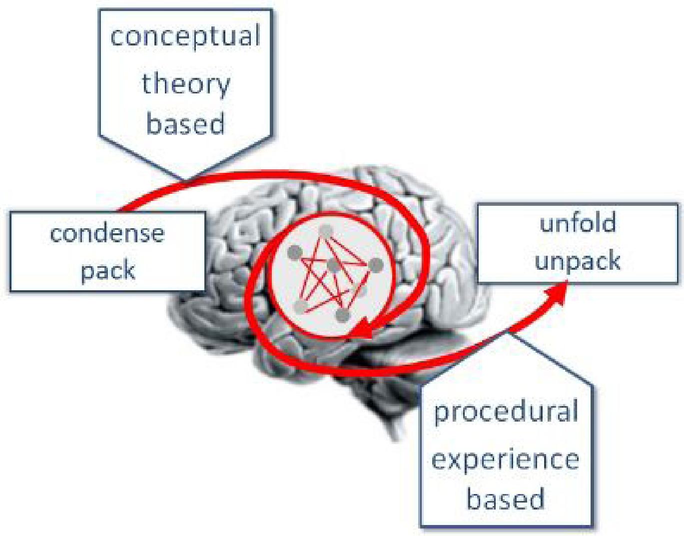

Figure 2: Dealing with the limited resources of the working memory: the dual dynamics of chunking involves condensing and unfolding of concepts in reasoning.

Another challenge in the inquiry cycle refers to the use of tools that depend on the domain of scientific investigation. They are required to assist our limited cognitive and perceptual resources. On an instrumental level, suitable tools are required to prepare and to interact with the systems of interest. On the theoretical level cognitive tools support modeling processes. Here the symbolic language of mathematics comes into play providing a wide variety of mathematical instruments that assist in modeling the observed structures and processes and in describing them quantitatively. In theory, mathematical tools reduce the cognitive load as they externalize part of the modeling processes (for instance computer program executing routine calculations). In practice, unfortunate to many learners, the use of mathematical language in science results in the opposite and tends to increase the cognitive load of the subject. To a great degree, this difficulty arises from detaching abstract mathematical symbols, definitions, formulae, operators and furthermore advanced concepts from processes that relate them to the real word. The grounding of mathematics in concrete experience is often neglected or even deliberately suppressed in teaching. Only few renowned mathematicians voice their critique on the underlying formal scholastic tradition in teaching mathematics [20].

Using central tenets from embodied and from grounded cognition could help in reducing the cognitive load of mathematical tools in scientific modeling. Embodied cognition is based on the assumption that human cognition, including mathematical conceptualization, argumentation and proof, is embodied relying upon concrete experience from the physical world [21,22]. Grounded cognition elaborates the idea that symbolic operations are based in the brain's modal systems [23]. Cognition involves dynamical processes that link perceiving, acting and reflecting. Knowledge embodied in, or linked to, perceptual and motor states plays a major role in creating and unfolding mental models, which are relevant for planning, controlling and evaluating (potential and real) actions. Building up and unfolding mental models is common to everyday reasoning as well as to scientific argumentation. It underlies anticipating aspects of future developments.

In contrast to the alleged abstract character of the symbolic language used in mathematical and scientific modeling there are no abstract symbols in our heads. They obtain their meaning through multiple links with concrete experience, using patterns of reasoning grounded in bodily experience from the sensory-motor system. In agreement with the chunking model the abstract and condensed constructs are conceptualized and unfolded in concrete terms. Different modality specific areas are activated when our brain activates concepts. Accordingly, there is no fundamental difference between everyday thinking and abstract scientific reasoning. Both depend on concrete experience in simulating, predicting and evaluating options for acting. From the perspective of embodied cognition, it is evident that hands-on learning and approaches that immerse learners in uncommon factual or fictional worlds should be beneficial to learning.

However, in hands-on learning the minds-on part is not an automatism. The educational efficiency of such a setting critically depends on providing adequate ways to reflect the concrete experiences and relate them to a more general theoretical framework. Quite similarly, for a successful implementation of inquiry based teaching the reflective part must be assisted by adequate methods of teaching and educational design to foster students in linking their experience with theoretical ideas and their restructuring and refinement. Learners tend to favor the more comfortable procedural mode at the expense of the analytic and reflective mode. Therefore, they need guidance in reflecting and generalizing their views in terms of the relevant domain specific principles. Accordingly, teaching requires a reflected orchestration of bottom-up and top-down methods, a balance between autonomous construction on the side of the learners and effective instruction on the side of the teachers. The balance depends on the subject and the degree of experience of the students (Figure 3).

As a general prerequisite, this approach needs more time than actually provided in most of the time-tables to fully unfold its potential. Lack of time to adequately engage in the inquiry cycle can be considered one of the reasons why the traditional use of experiments in science teaching largely fails. It does not improve conceptual understanding, although experiments are beneficial to motivation and raise the interest in the subject. This also limits the potential of inquiry based outreach projects such as out of school laboratory programs although their motivational impact can be considerable [24].

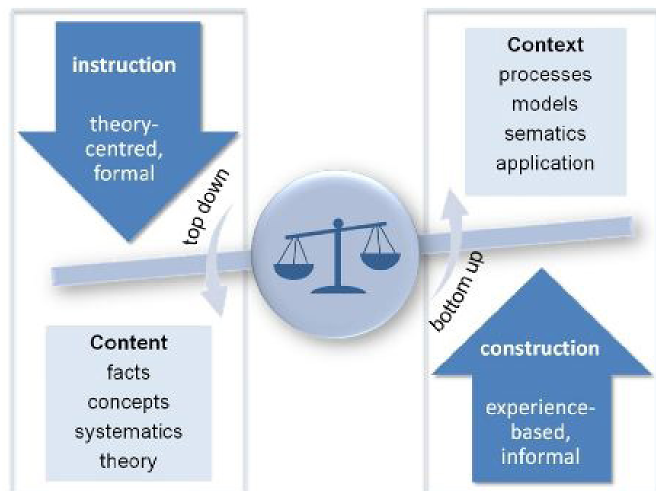

Figure 3: Balance between instruction and construction in teaching.

In the subsequent examples, we present hands-on and model based approaches to teaching ideas from nanoscience that conform to the sketched dual framework of interlinking conceptual and procedural knowledge. Efficient science learning critically depends on teaching methods that facilitate and reflect both modes of knowing by thoughtfully interweaving instruction and autonomous construction. We elucidate the productive role of experiments as engines of intuition that promote procedural knowledge on par with conceptual knowledge. The experiments investigate the properties of macroscopic systems that can serve as models for certain structural or functional aspects of nanosystems. By activating and reflecting meaningful analogies, they can open up new vistas and conceptual links to distant subjects and abstract ideas.

From the demands of abstraction, the experiments range from introducing the basic ideas of scale dependent properties to teaching more advanced topics such as visualizing and interacting with the invisible nanoworld, suited for the upper secondary or the introductory college level. While the first part sets the focus on physical and technical aspects, the second part brings biological ideas to the foreground and highlights the conceptual unity of organizing principles beyond the complexity of biological nanomaterials. With these provisions in mind the readers should approach the following examples and adapt them to his or her teaching.

Size Matters: Confronting Fictional Travels to Nanoworlds with Experimental Facts

A nanometer (nm) is one billionth (10^{-9}) part of meter. Nano-sized systems possess characteristics highly different from our macroscopic world. Their behavior depends on size. At the naoscale the grainy structure of matter and related thermal and quantum effects come to the foreground. In order to acquaint students with the idea that properties can depend on size we start from wave phenomena like sound and light that have an immediate meaning from everyday experience. Moreover, wave phenomena provide a bridge to nano-imaging by scanning tunneling microscopy, a method that depends on wave properties of electrons.

In order to elicit students' ideas, the approach can be framed in narratives about fictional literary or movie contexts that draw on the idea of shrinking persons to miniature size [25]. The prefix nano is of Greek origin and means dwarf. In the famous novel "Gulliver's travels" the hero visits the dwarf-world of Lilliput people. They are downsized by a factor of 12 and possess all the characteristics as full-sized humans. Gulliver is reported to have no problems learning Lilliput language (Figure 4). Is that possible under the premise that dwarf phonation is based on a proportionally scaled down version of our own system?

This is a question that can be tested and resolved in hands-on and ears-on ways. The frequencies of musical instruments and of speech are based on resonant oscillations which in turn depend on size. Students easily find out that the frequency of pipes increases with decreasing length in a reciprocal fashion. This is an example of inverse proportionality. Scaling down by a factor of 12 scales up the frequencies by the same factor.

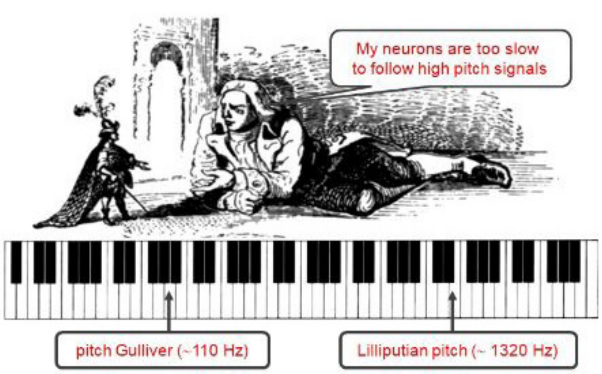

Figure 4: Is it reasonable to assume that was Gulliver able to learn Lilliput language?

With the sound capabilities of computers or smart phones it is easy to investigate how language sounds if its spectrum is scaled up by a factor of 12. In music, this shifting of notes to another key is known as transposition. Suitable sound editor programs allow students to record and transpose speech. Scaling up by small factors results in the well-known Mickey Mouse effect; the higher pitched speech sounds funny, but it is still intelligible. However, language becomes incomprehensible after a transposition by a factor of 12 (3.6 octaves). The prosody is still there but the meaning of the utterance cannot be decoded. Students learn that without technical means we would be unable to understand Lilliput language. Bad news for movie plots that involve shrinking people! To fully understand the loss of intelligibility is a more involved task. It requires knowledge how our brains decode speech. One channel of speech processing depends on transmitting and analyzing the periodicity of signals in real time (periodicity pitch). The fundamental pitch of human voice cords ranges between 100-200 Hz. Scaling up shifts the pitch beyond 1000 Hz. Our neural signals are too slow to reproduce the periodicity of the high-pitch signals. Only their intensity is processed.

Another instance worth of hand-on investigation is vision. The Gulliver novel says that as a consequence of the tininess of their eyes Lilliputians see objects that are near with great exactness. Again, this claim is based on the idea of proportional scaling. It is in accord with geometrical optics. Light propagates in straight lines and the rules of trigonometry allow for proportional up- or downsizing. At the time of the novel's origin it was not yet common to consider light a wave phenomenon. Due to its wave nature, the width of a light ray has a lower limit. This limit is literally tangible using our fingers and the light beam from a laser pointer (lowest power for eye safety reasons).

The hands-on attempt to confine light beams provides the relevant hint. The wave property of light sets a lower limit and degrades the performance of tiny lens eyes. As a hands-on experience student can try to make the beam smaller by passing it through the gap between two fingers. Before the gap closes, the beam widens. The widening is the main effect. It is accompanied by light and dark bands that result from interference of the light waves. Usually, this experiment carried out in a more "professional" way using a slit with variable width. However, the hands-on version is quite enlightening, as it gives a feel for the unexpected widening reciprocal to the input action. This incompatibility with the ray model is resolved by the wave model of light propagation. The wave nature of light brings about diffraction effects that widen the bundle.

Theory shows that the widening is proportional to the wavelength and inversely proportional to the width of the slit. Two different scaling principles collide. The resulting behavior is schematically shown in figure 5. Starting from an initial large spread the beam width is narrowed proportional to the width of the gap (grey dotted line). Diffraction effects result in a reciprocal widening. Their combination results in a minimum bundle width, which is roughly in the order of the wavelength (red line). The smaller pupil apertures of Lilliput eyes cause greater widening. The minimum angle that they can resolve is a factor 12 worse than in Gulliver's optical system. In a similar way the aperture restriction of optical microscopes limits the minimum size of visible structures to roughly half a wavelength, 150 nanometers at most. It is impossible to take a photo of atoms (typical size 0.1 nanometer) with an optical microscope. Suitable "eyes" for the nanoworld and instruments for intervening on the level of individual atomic or molecular particles require new design principles.

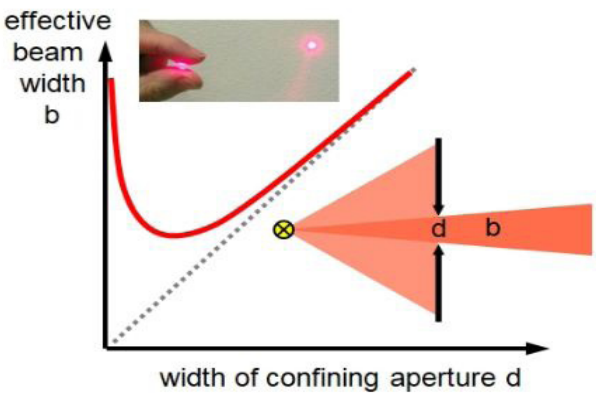

Figure 5: Is Lilliput vision more acute than ours?

Interacting with the Unknown: The Walking Stick Model of Knowledge Acquisition and Principles of Nano-Imaging

For millennia, atoms were considered theoretical entities that nobody was able to see and grasp. With the advent of Scanning Tunneling Microscopy (STM) it became possible to create visualizations of atoms or molecules and to manipulate individual particles. Figure 6 shows an STM-image the so-called quantum corral, a man made circular arrangement of 48 iron atoms on a copper surface. It has become an icon of the new field demonstrating the design of a nanosystem atom by atom [26]. Different versions of the corral made their way into textbooks and popular presentations.

What kind of reality is depicted in the corral image? Quantum physics has shown that material particles have wave properties similar to light. How then is it possible to create images of atoms that seem to "sit there" like macroscopic objects? Inside the circular confinement of the atomic "fence" extended wave patterns are present reminiscent of water waves in a pot or a frying pan. Obviously, the quantum corral shows both particle and wave like aspects in a single picture. How to reconcile these seemingly opposing structures with the conception of atoms in the heads of students? Are atoms tiny lumps of matter like marbles? Do they display a structure like miniature planetary systems according to the Bohr atomic model, which is omnipresent in textbooks and in the heads of students? How does the wave model of particles fit in?

Figure 6: The clash of particle and wave models in the nanoworld. How to interpret structures in the STM image of the quantum corral and relate them to the students' models of atoms?

An adequate interpretation requires conceptual knowledge about the imaging process and the wave nature of matter. In order to stimulate reflections on how to visualize the invisible and how to gain knowledge about the strange world of atoms and quanta, we suggest recurring to epistemological discussions from the early days of quantum physics. At that time researchers were deeply troubled by the apparent clash between the world view of classical physics and the new theory of quantum phenomena. Niels Bohr, one of the founders of quantum theory, created an appealing metaphor to facilitate a better comprehension of the new epistemic situation that transcended the concepts known from the classical physics of macroscopic objects. He compares a classical observer inspecting the invisible quantum world to a person using a walking stick to find the way in a dark room [27].

At first sight, the cane 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. It depends on our grip of the cane where to place the dividing line between subject and object. If it is grasped firmly, the cane 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. With firm grip it is possible to determine the position of objects. Feeling the momentum of the objects' motion requires the loose grip mode. Contrary to classical physics, a simultaneous measurement of complementary variables such as position and momentum is impossible in the quantum domain. The above hands-on experience with laser beams embodies a related incompatibility. The attempt to confine light rays results in the opposite effect of widening. It represents a general principle that also applies to matter waves. Any effort to confine material particles is counteracted by their wave properties.

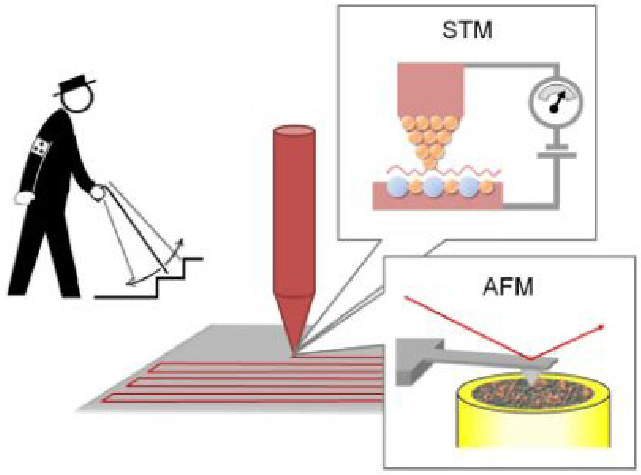

Figure 7: The walking stick metaphor and the principle of scanning probe microscopy. Two methods are shown: Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM).

The walking stick metaphor depicts various issues of intervening with and gaining knowledge about the invisible nanoworld. It demonstrates the arbitrariness of the cut between subject and object. Moreover, it is an illustration of the complementarity between the measurement of position (firm grip) and momentum (loose grip). It stands for the experimenter's freedom of choice of selecting which mutually exclusive properties of the quantum world to measure in an experimental setup. Moreover, in the present context, it nicely visualizes the principle of scanning probe microscopy methods that underlie nanoscale imaging. These methods create images by scanning nanoscale structures systematically line by line with a probe that ends in a fine tip similar to the explorative scans of a walking stick (figure 7). Depending on the method, different ways of interacting are used to obtain information about the structures under investigation. Scanning Tunneling Microscopy (STM) is based on measuring the current between tip and surface. Atomic Force Microscopy (AFM) detects interaction forces via the bending of a tiny elastic beam. Conceptually, the STM method is more demanding as it explicitly depends on quantum effects in the electronic current, while AFM is largely in line with force detection schemes in the classical world. We begin with a classical model that relates the principles of Scanning Tunneling Microscopy (STM) to experience.

Hands-on Nanoscience: Imaging and Imagining Atoms

An adequate interpretation of the STM images depends on understanding quantum principles and the mapping process, which differs fundamentally from conventional optical imaging and magnification techniques. STM combines classical engineering with quantum physics. The classical part refers to scanning surfaces at atomic scales with a tip-shaped probe that ends in a single atom. Its motion is controlled by a piezoelectric drive. Quantum physics comes in by measuring the tunnel current between tip and surface that results from applying a small voltage between both. A current can flow before tip and surface get into full contact. It is called tunnel current as the electrons flow although there is an isolating gap between the two conductors. The term tunneling refers to the analogy of passing a mountain barrier straight through without sufficient energy to climb up the barrier.

A few teaching models exist that demonstrate the method by mechanically scanning macroscopic structures, using marbles or table tennis balls to represent atoms [28,29]. The mechanical models neglect the special quantum nature of the interaction between tip and surface atoms. Moreover, they support naïve views of atoms as tiny specks of matter made up from portions of a continuous material stuff with a well-defined mechanical shape. Such concepts are also promoted by the photorealistic rendering of the image that adds color, shadows and light reflections, giving spatial depth to the structures. While these attributes enhance the aesthetic appeal of the images, they tend to confuse inexperienced spectators. Properties as shape, hardness, color are macroscopic and have no counterpart on the level of single atoms. They emerge on a collective level. Collective properties and emergence are advanced multi-faceted concepts that require experience and time to ripe in the mind of the learners.

In order to discuss and clarify the nature of STM images, students can design and explore macroscopic models. In view of the conceptual gap between the macro- and the nanoworld, a model-based approach might appear futile due to the quantum nature of the underlying interactions (tunnel effect). Nevertheless, it is possible to devise macroscopic similes of the imaging method by taking advantage of quantum-classical analogies between matter and sound waves. The scattering and tunneling of electrons in STM can be explained intuitively in the wave picture. Electrons have wave properties. The electronic wave functions reach out over confining barriers. They overlap progressively in the near field when the tip approaches the sample. The tunnel current that can flow before close contact depends on the overlap of the wave patterns. The tunnel current increases exponentially with decreasing distance. In the classical world, the overlap of states corresponds to a resonance. The resonance analogy is the guiding concept to conceive a sound-based imaging system.

Starting from this idea, the imaging principle is readily accessed with a one-dimensional hands-on scanning model. Figure 8 shows the device for manually scanning a row of yoghurt bottles [30]. The sound probe is constructed by extending an earphone capsule with a narrow metal tube. In order to ease the scan, the probe is attached to wheels from a Lego set. Two rails guide the motion. The probe is connected to a frequency generator and tuned to the resonance frequency of the bottle. It is possible to find the position of the resonators without any technical apparatus merely by listening. The loudness of the resonant mode increases as the probe approaches the bottle's mouth. In order to measure the sound field, a microphone is coupled to the probe. Figure 8a shows the sound signals from a linear array of 5 bottles scanned manually. Each bottle is identified by a maximum response. This compares to locating individual atoms in STM. The sound probe is frequency selective. The third bottle in Figure 8b is partly filled with water. It remains undetected because it is out of resonance.

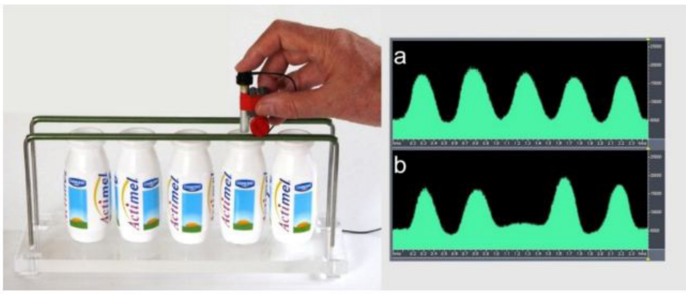

Figure 8: One-dimensional acoustic scanning of resonating yogurt bottles.

These experiments are sufficiently simple to be carried out as a home project by using a smartphone as sensors and display [31]. A more professional version of the experiment to create high quality images can be given as a project in technological design or in IT-courses to more advanced students. It includes a computer linked to a graphic tablet to collect, analyze and visualize measurements. The graphic tablet is used as a position sensor in a two-dimensional scanning system. The idea is straightforward: A computer program stores the sound field data from successive scans point by point and line by line in a two-dimensional data matrix. Students can explore various ways to visualize the data by computer graphics. The full three-dimensional rendering in figure 9 creates a topographic impression by using colors, shades and light effects. The match between the acoustic and the STM images is amazing. An unbiased observer cannot tell if the hexagonal structures represent a regular arrangement of surface atoms or a macroscopic array of resonating bottles.

In contrast to STM images the model allows for to comparing the 'real' system with its acoustic mapping. The result is quite different from mechanical localization according to the walking stick model. The image reveals feature completely different from tangible reality. The peaks indicate the maximum response above the bottle's mouth. At that point, no tangible matter is present, but the coupling with the bottle resonance is optimal. Detecting the acoustic maximum corresponds to localizing individual atoms by the STM-tip. The vacancy in the structure on the computer screen does not show a missing "atom". It represents a different sort of atoms simulated by a bottle out of resonance.

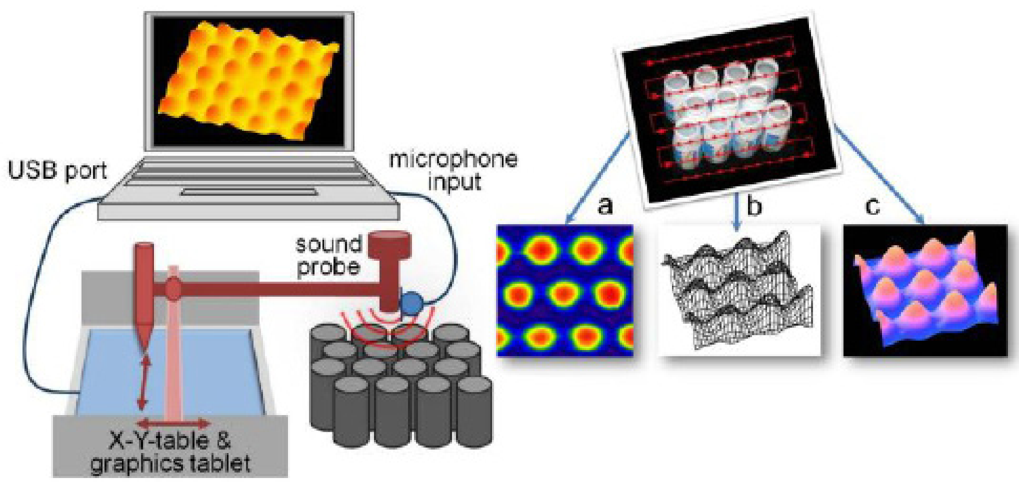

Figure 9: Principle of the acoustic imaging setup and three different data visualizations: (a) contour plot, (b) mesh plot, (c) three-dimensional rendering.

The frequency selective acoustic imaging corresponds to the spectroscopy mode of STM which selectively interacts with electron states depending on their energy. The acoustic frequency is related to the voltage applied to the STM tip. The power of the acoustic response corresponds to the tunnel current which in turn depends on the quantum mechanical probability distributions [32]. The perfect match between imaging with sound waves in the model and electron waves in STM is based on the analogy between the acoustic wave equation and the wave equation that governs the behavior of electrons (time independent Schrödinger equation). Due to this analogy, electronic transport and scattering phenomena can be simulated with acoustic waves. Conceptually, the acoustic models elucidate the nature of STM images and convey the productive tension of imaging and imagining an invisible reality while restricting the theoretical background to a minimum. What we can see and grasp (the intuitive reality) shows only the surface or the interface of a more abstract reality that is hidden to our senses. It is only amenable to imagination, informed and refined by instrumental and theoretical knowledge according to the inquiry cycle.

The Sounds of the Nanoworld: Classical Analogues of Near Field Imaging

By addressing the role of classical-quantum correspondences, the above method can be refined and extended to elucidate matter wave dualism on a level suitable for introductory quantum physics. Moreover, the analogy is also productive in the opposite direction. The concepts that it embodies can contribute to a more profound understanding of hearing processes. In its essence, the high spatial resolving power of STM is a product of near field imaging. The relevant interactions between the wave fields are restricted to the immediate vicinity of the probe tip. The idea of near field imaging is already evident in the above one-dimensional scanning device. Sound waves with wavelengths of 30 cm are used to localize much smaller structures. In conventional optical imaging this is not possible. The aperture restriction to light bundles (cf. figure 5) sets a lower limit of half a wavelength to the minimum size resolved by optical microscopy [33]. It took a long and road of theoretical and instrumental development to successfully devise near field imaging techniques for nanoscale systems.

However, the basic principle was around us all the time, largely unnoticed and concealed in everyday auditory experience. We take the phenomenon for granted without further reflecting the underlying highly sophisticated processes. Students can experience principles of near field imaging in hearing by a simple self-experiment (Figure 10). Create a noise by rubbing two fingers and move the sound source in the vicinity of one ear. Close your eyes and block the opposite ear with the palm of your hand. By using only one ear it is possible to locate and to track the noise source in the near field.

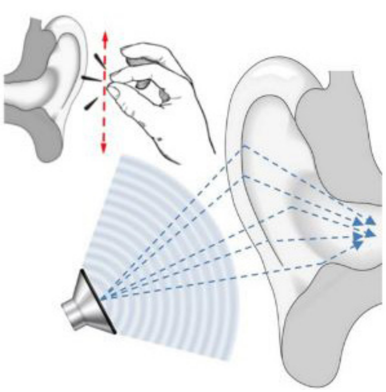

Figure 10: Localizing the sound of rubbing of fingers is a natural experience of near field imaging, based on multiple scattering of sound waves at the outer ear.

The experiment highlights an intriguing instance of everyday biophysics. Many textbooks describe only binaural processes in direction hearing and locating acoustic events. However, monaural mechanisms count as well. Monaural auditory localization exploits the transmission characteristics of the outer ears for localizing spectrally rich sound sources. The complex shape of the pinna plays a crucial role. It guides and resonates with the incoming sound waves in a complicated manner. The scattered partial waves propagate towards the eardrum and interfere depending on their phases. Thus, the perceived sound intensity varies considerably depending on the frequency and the direction of the incoming sound. We have learned by experience to associate the resulting changes in timbre and loudness with the direction and the distance of sound sources. Thus, our acoustic sense creates an inner auditory image of the sonic world.

The explanation of monaural localization of sound combined with conceptual knowledge about the wave nature of electrons is helpful in interpreting the quantum corral image in figure 6. It resolves the issues related to the seemingly contradictory coexistence of particle and wave like structures in the same image. Moreover, by systematically exploiting the similarities in the scattering of sound and matter waves it is possible to devise a fully transparent acoustic model of the quantum corral.

Figure 11 shows a possible design using ultrasound for scanning to keep the dimensions small [32]. The acoustic corral model is made of an aluminum disc with 16 concentric bore holes. The holes act as resonators and secondary sources for scattered sound waves. An ultrasonic source is used to scan the structure from above. In 2 cm distance below the disk another metal plate is mounted with a fixed microphone in the center. The resulting sandwich structure provides a planar confinement of sound that simulates the propagation of electrons along the surface of the coral structure. The bore holes act as acoustic cavities that resonate with the sound frequency. The ultrasound propagates to the microphone below through the cavities.

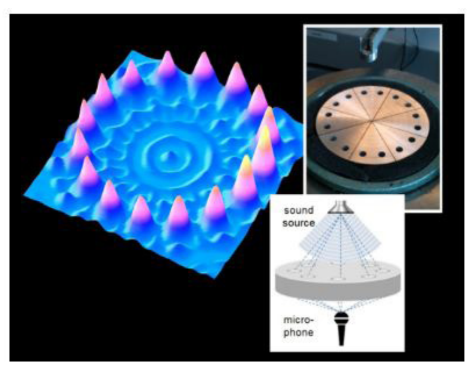

Figure 11: The acoustic corral - a classical model of the quantum corral. The acoustic setup and the scattering scheme of sound waves are shown on the right.

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Students can discuss the setup in figure 11 and describe the parallels to monaural localization due to multiple scattering of sound waves by the structures of the outer ear. In the acoustic corral, a number of regularly arranged resonators take part in the scattering processes. The outer ear also has a few more irregularly shaped cavities. In both cases localization depends on interference, because sound signals are superposed (added up) in the sound detector after taking different paths. Moreover, students can compare the acoustic corral image with the quantum corral in figure 6 and reflect about the parallels especially with respect to wave and particle aspects of matter.

The quantum corral reveals a strange reality that we describe in everyday language by using a mixture of wave and particle models. The Fe-atoms appear as discrete, localized objects. They seem to stand out from a continuous sea of circular waves. The latter represent standing wave patterns of the conducting electrons at the copper surface which are confined to the interior of the atomic "fence" made up from the Fe-atoms. However, STM images display neither waves nor particles; they visualize data. We impose wave or particle models to give meaning to the perceived patterns. The acoustic corral image displays quite similar patterns. Without knowing how the image was created we would tend to give an interpretation in terms of localized particle-like and extended wave-like structures in accord with the quantum corral. However, as the acoustic system is fully transparent, we know that the circular arrangement of peaks results from the bore holes in the upper plate. These resonating cavities stand for the circular fence of Fe-atoms in the quantum corral. Both give rise to a strong localized signal. Similar to the resonating bottles in the preceding section the peak response indicates immediate proximity to the scanning probe.

Inside the circle, an extended pattern of concentric waves indicates interference. The sound signals from the ultrasonic transmitter reach the microphone via different paths through the bore holes. This gives rise to a standing wave pattern with maximum or zero sound pressure depending on the relative phase of each individual contribution which varies during the scanning process. In this way it is possible to simulate acoustically the resonant detection of the Fe-Atoms and the scattering of surface electrons inside the quantum corral. Electrons are injected by the STM probe and propagate along surface states. They undergo scattering at the fence atoms which gives rise to the observed standing wave pattern of probability density inside the circular confinement.

The successful acoustic analogy contributes to clarifying conceptual and philosophical issues on the new role of visualizations in nanoscience. STM images inspired numerous discussions about their nature as they display a quantum reality that transcends the limits of visual experience. The veracity of the presentations was questioned as they include additional elements to enhance their visual appeal that are alien to the nano-domain. Moreover, as they unite two opposing views such as particle and wave aspects they are often compared with objects of abstract art [34]. 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 model experiments provide a clear answer. While images transcend naïve photorealism, they are in accord with views from another sensory modality. In auditory scene analysis we unconsciously apply imaging strategies based on multiple scattering of waves that are closely related to near field imaging with STM! Our mental image of the auditory world is highly different from the colorful visual scenario, less detailed but sufficiently precise to inform us in a separate channel about events outside the visual field. The acoustic corral model shows how the strange reality of nanoworld images with its hybrid mixture of particle-like and wave-like structures can be resolved satisfactorily via acoustic analogies and principles of near field imaging. Instead of "seeing atoms" in the STM scans it is more adequate to think of hearing atoms in the sense of localizing dynamical entities by the scattered wave patterns. Loosely speaking, STM images can be considered visualizations of the inaudible electronic sounds of the nanoworld.

The present examples elucidate the function of experimental tools as engines of knowing that promote conceptual development. This re-balancing in the role of tools on par with concepts is also a characteristic trait in the rise of nanoscience. In line with the dichotomy of conceptual and procedural methods of knowledge generation one can discriminate between two kinds of scientific innovations, those driven by new tools and those driven by new concepts [35]. Nanoscience clearly belongs to the first category. The rapid development of the field demonstrates the role of instrumental devices as facilitators and catalysts for new insights. It reveals the close interweaving between the productive function of tools and their epistemic role in promoting innovations and generating new knowledge. The invention of the STM triggered off a spectrum of different devices to interact with systems on the nanometer scale [36]. The instruments opened the doors to the nanoworld, not only on a technological but also on a conceptual level. The next chapters highlight the role of another scanning probe method, the atomic force microscope and its use in providing insight into the nanomechanics of living systems.

Models of Force Microscopy: Exploring Life's Nanomechanical Secrets

Similar to the STM an Atomic Force Microscope (AFM) consists of a fine tip that can be positioned reproducibly along 3 spatial directions on the nanometer-scale (Figure 7). It measures the forces on the tip by detecting the deflections of a micro-fabricated beam to which the tip is attached. Devising an AFM teaching model is rather straightforward due to the classical nature of the force detection scheme that depends on deforming a body [37].

Similar to the walking stick model of intervening with an invisible world the system can be used in a static contact mode or in a dynamic oscillating mode to investigate objects and processes on the nanoscale. We focus on the use of the AFM in detecting the forces as a function of position during extending or contracting individual molecules. This mode of operation is called force spectroscopy. Figure 12 shows a student-made teaching model of the AFM. The setup corresponds to an extensometer known from tensile testing in material science. The ends of the sample are attached to a graphics pen and a flexible small beam. A strain gauge glued on the beam measures the deforming force while the pen on the graphics tablet serves as position sensor. The pedagogic appeal of the instrument rests on combining hands-on experience of extending objects with a simultaneous display of force–extension graphs.

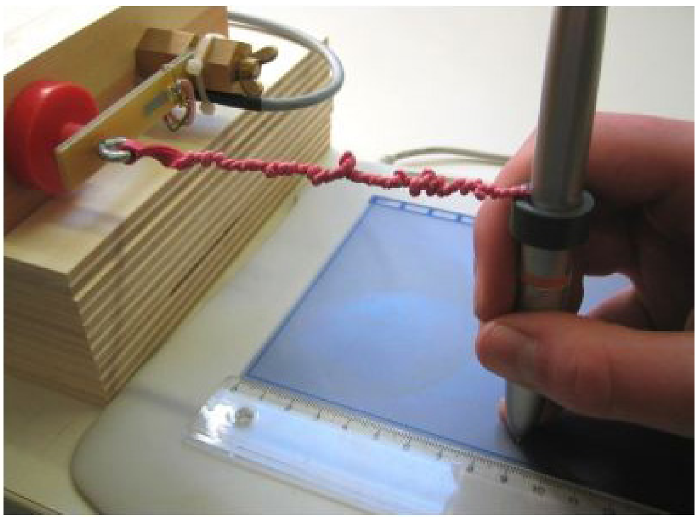

Figure 12: Graphic tablet and force sensor for force-extension measurements as a teaching model for studying principles of atomic force spectroscopy of protein molecules.

The force-action schema underlying the AFM is related to our immediate experience of using muscle force to deform or move objects. The more force we apply the greater is the resulting action. For small extensions the elongation of elastic bodies is proportional to the applied force. This approximate behavior is codified in Hooke's law, a core subject of physics teaching conveyed to students by extending elastic springs. However, the elastic properties of biologically relevant molecules such as proteins or DNA are highly different from the Hookean spring model. Force microscopy helps in exploring this strange behavior and hands-on models assist in elucidating nanomechanical processes in living systems.

Proteins are biological polymers made up from 20 different amino-acids. Up to several hundred amino-acid building blocks are linked to form a linear polypeptide chain. After synthesis, the chain folds into a macromolecule with a complex shape and a typical size of a few nanometers. Proteins can be considered biological 'nanomachines' that sustain life by processing matter, energy, and information. With the AFM in the spectroscopy mode it is possible to measure force-extension curves of protein molecules. The study of titin is paradigmatic [38]. This is a "giant" muscle protein, made up from a linear chain of another protein species with globular structure (immunoglobulin). One end of the protein is fixed to a surface, and the other end is attached to the tip of an AFM (Figure 13). Extending the molecule produces a saw-tooth pattern of several largely identical force peaks related to the stepwise unfolding of the globular domains. The unraveling of each domain produces a force peak after which the force decreases although the molecule is extended further.

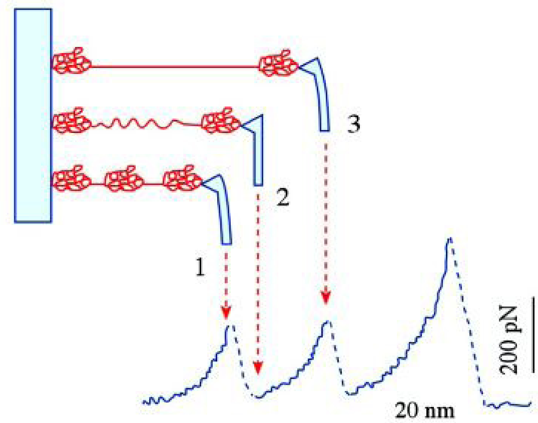

Figure 13: Force spectroscopy of titin molecules (Bao & Suresh (2003), graphics modified) [39].

This is highly different from the monotonic increase of the restoring force during stretching elastic springs. The elasticity of materials such as steel depends on stressing the binding forces between particles which changes the inner energy of the system. For short, these solids can be labeled "energy springs". The elasticity of soft materials such as rubber and biological tissues includes another mechanism based on entropy (temperature dependent molecular disorder). They represent "entropy springs" [40]. The force required for stretching the globular protein section does not act on molecular bonds but counteracts entropic processes that tend to keep the molecular chain in a tangled dynamic state of maximum molecular disorder. Similar to the links of a chain, smaller sections of the molecule are free to rotate without stressing bonds. Thermal energy drives this irregular motion.

During the extension of an individual globular protein domain, the elastic force increases as the molecule is stretched into a less entropic largely straight conformation. After disentangling the high entropic globular state, the force drops to nearly zero, although the stretching of the molecule continues. Thus, titin filaments can be considered strange entropic springs that repeatedly soften under extension. They act similar to molecular shock absorbers dissipating energy step by step. Many entropy springs working in series prevent the energy springs (chemical bonds) from breaking. The resulting superelasticity makes muscle fibers more resilient to mechanical strain.

On the basis of this theoretical background students can create and explore hands-on models of protein folding. Creative play with rubber bands is highly inspiring and conveys central ideas. It requires a few materials (and mental) twists to transform a rubber band into a strange spring that exhibits irregular force spectra. Stretch a rubber band to a certain length and twist it a few dozen times. Prevent the band from unwinding and shorten the length gradually. At certain critical points, new twisted loop-like structures will develop spontaneously and transform the one-dimensional string into a three-dimensional object (Figure 14). The twisted loops can be created and annihilated in a reproducible manner when the processes are carried out slowly. Stretching the band makes them disappear. They will reappear at the same positions during slowly relaxing the band's tension. The transitions are accompanied by jumps in the applied force that can be felt. Force spectroscopy measurements provide a quantitative account and reveal highly irregular force variations during contraction and extension. Every act of entangling or disentangling a twisted domain is connected with a spike in the force spectrum, resulting in a saw-tooth pattern that resembles the unfolding of the globular domains in the titin pulling experiment. The force not only depends on position but also on history of the process (hysteresis), depicted by the arrows.

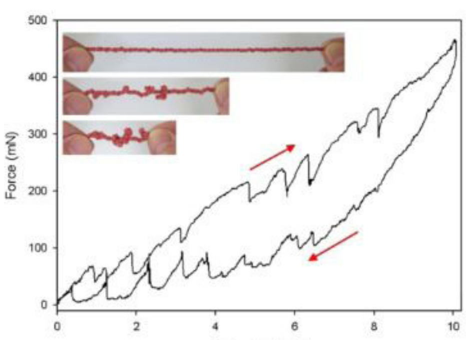

Figure 14: Force-extension measurement of a twisted rubber band. The inset shows the unfolding of typical shapes after relaxing the tension of the twisted band.

The hands-on experience with tangled rubber bands helps in untangling basic ideas of protein folding, which is kind of a miracle, even to hard-boiled reductionists. In a proper environment, the linear polypeptide chain transforms into a three-dimensional object. It can act as a dynamical system with passive and active functions, relevant for sustaining processes that keep cells alive. For instance, proteins can provide mechanical stability, act as biochemical enzymes, valves, switches, molecular motors and much more. Potentially, the structure of the working protein is already inherent in the linear chain, encoded in the sequence of the amino acids. Its function is activated only after folding to its final structure.

The unfolding of complex functions via protein folding is a fascinating example of molecular self-organization driven by temperature and chemicals of the surrounding medium. The twisted rubber provides a mechanical basic model for the emergence of new properties in life's molecular machinery at the nanometer scale. It makes the creation and annihilation of new structures upon changing external parameters literally tangible. In a proper environment (i.e. at critical tensions of the band) the one-dimensional twisted string folds into a three-dimensional object. Due to material imperfections in the band, the emerging kinks appear in a seemingly 'preordained' manner. The resulting three-dimensional tangled object can be recreated in a largely reproducible way by repeating the experiment with the same boundary conditions. The reproducibility resembles the reliable unfolding of the three-dimensional structure of the functional protein encoded in the linear sequence of the amino acids.

Creative Twists: A Toy Model of Packing and Unpacking Genetic Information

The rubber string experiment is inspired by playfully exploring structure formation in common materials and transferring the ideas to nanoscale shape transformations in biomolecules. It presents a rather coarse picture of protein folding restricted to structural aspects. The dynamic component inherent in entropic disorder is missing and difficult to simulate in that context. However, the creative play with the rubber band model can be extended in a different direction by focusing on transformations of geometric forms. These more refined considerations reveal general principles that also underlie shape transformations of DNA molecules, the carrier of genetic information. The nanomechanics of DNA and the geometry of related molecular aggregates play a fundamental role in genetic and epigenetic processes [41].

Different from proteins, DNA molecules are less flexible. The double helix of the sugar-phosphate backbone is linked by complementary base pairs, whose sequence represents the genetic code. In a continuum model that neglects all molecular details the mechanical behavior of DNA can be compared with a thin elastic rod. Again, students can use a rubber band to investigate properties of the elastic rod model and study the geometry of structures that result from shape transformations. A careful systematic approach starts from a full twist (360 degrees) of a pre-strained band. After relaxing the tension, the band develops a spiral coil until it gets into self-contact and one complete coil is formed (Figure 15). Starting from 2 full twists could theoretically result in two separate loops. In practice, at the point of contact, the two string sections form an additional mutual twist. In that way, more initial twists of the individual string result in multiply intertwined string sections comparable to plying yarn.

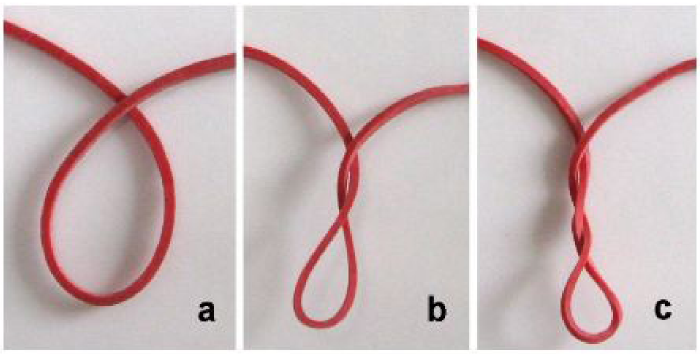

Figure 15: Coiling of a twisted rubber band after relaxing the band's tension starting from one initial twist at left. The number of twists increases by one from a-c and results in an equal number of intersections.

Similarly, DNA molecules can develop multiply twisted structures called supercoils. In spite of their complex shape there is an inherent topological conservation law. As one twist is transformed into one coil and vice versa, the sum of twist and coils remains constant during a transformation. The number of coils, the so-called writhing number, is not immediately evident; it corresponds to the number of intersections in a planar projection. Without addressing more involved topological and energetic aspects, the present hands on mechanical model suffices to make the basic phenomenology of DNA forms and its function in the mechanics of genetic processes tangible.

In everyday life, the supercoiling effect is a nuisance as we all know from dealing with tangled cables or garden hoses. In contrast, biological evolution exploited tangling and untangling DNA in highly productive ways. Without folding and unfolding DNA strings, no higher organisms with complex genetic programs would exist. DNA is one of the longest naturally occurring molecules. This poses a packaging problem. How is it possible to confine for instance human DNA strands with a diameter of 2 nanometer and a total length of 2 meter in the micrometer-sized cell nucleus? Again, the rubber band toy model triggers the relevant theoretical ideas that apply to packing and unpacking genetic information on different levels.

The challenge is not the small volume per se but the sequential nature of the genetic code. The condensation must occur in such a way that relevant subsection of the much longer strands can be readily accessed to read out genetic information for transcription processes that finally result in protein synthesis. Evolution has solved this task by orchestrating a system of folding string-like structures that consist of DNA strands linked to proteins. This molecular aggregate is called chromatin. The condensation of chromatin loops takes place several times, giving rise to different hierarchically organized levels of structures in packaging genetic information [42]. The bare DNA helix presents the first level of organization (Figure 16 a). On the next level, DNA loops are formed. They can wind around proteins (histones) and form periodically repeated structures 11 nm wide, reminiscent of pearls lined up on a string (nucleosomes). The parl-chain structure condenses spirally or in zig-zag to a 30-nm strand of chromatin. The chromatin strand is further folded to domains 300-700 nm wide. These structures combine to chromosomes that can be seen in optical microscopes during cell division. In concluding the division, motor proteins transport the chromosomes into the nucleus where they exist in a closely packed phase.

Genetic expression and regulation requires accessing specific sections of DNA in the nucleus. The basic process of unfolding genetic information is to expose chromatin strings in order to bring them into contact with the transcription machinery. The twisted loop structure of the rubber band provides a mechanical intuition of how string-like information carriers can unfold and present information for further processing. The exposed parts dangle from the surface of chromatin into the space between chromatin compartments. The information is localized in the tip region of maximum curvature. In this way, the exposed genes can be read out by the transcription machinery that resides in the interchromatin space (Figure 16 b). The interaction of several loops can bring together information that was initially separated on the DNA strand. Depending on neighboring relations, information between different parts of the same chromosome or from different chromosomes can be combined. The three-dimensional landscape of chromosome territory inside the nucleus opens up an inexhaustible universe of genetic combination and regulation.

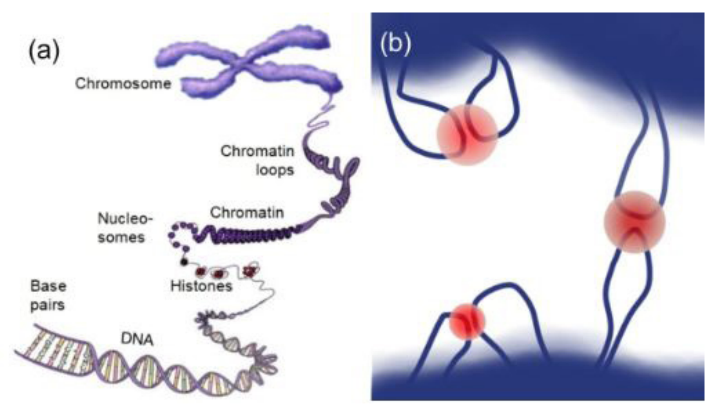

Figure 16(a-b): Hierarchical packing of genetic information in chromatin loops (a) and unfolding of chromatin structures in gene expression (b).

The rubber band experiment is an engine of intuition that embodies a variety of abstract principles. As a toy system it stimulates imagination and promotes modeling processes. In the present context, it provides a tangible model how twists in DNA can

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orchestrate life in a hierarchy of nested structures and networks of interaction. It helps to clarify principles of self-organization in living systems which are hidden beneath the enormous complexity of biochemical processes. Conceptually, the models connect two widely distant scientific domains, the field of mechanics, which traditionally investigates the inanimate world of macroscopic bodies, and the field of genetics which investigates living systems.

The basic model can be boiled down to a feedback cycle that interlinks the level of biochemistry with the level of mechanics. Biochemical processes act on the mechanical properties of DNA/Chromatin strands, which in turn act back on the biochemistry via transcription processes that synthesize new molecular products. The feedback cycle includes processes of upward and downward causation. It describes property emergence in complex systems. Mechanical properties such as elasticity do not exist on the level of atoms and small molecules. They emerge largely size dependent and define a new level of organization as a result of the molecular interactions (upward causation). In the opposite direction the mechanics of the DNA/Chromatin-strands controls biochemical processes (downward causation).

For many, it may come as a surprise that mechanical principles are relevant for genetics, a fact not yet acknowledged in biology curricula. This shift of perspective in genetic modeling is driven by the availability of suitable instruments to mechanically interact with systems and to detect forces on the nanoscale. On a conceptual level, the emergence of mechanical properties in sufficiently complex molecules is the reason that we can successfully use mechanical and even machine metaphors to describe the function of biological nanosystems. It is justified to speak of forces from pushing and pulling on molecules, and to consider macroscopic phenomena such as bending twisting and folding and unfolding. Moreover, it is more than metaphoric language to describe proteins as biological nanomachines, although they are highly different from man-made machines. Emergent mechanics on the nanoscale is also the reason why atomic force microscopy is conceptually intuitive. This is different from scanning tunneling microscopy, where successful modeling has to resort to wave phenomena to elucidate the principles.

Engines of Imagination and Knowing: Models, Analogies and Conceptual Reflections

The present approach to modeling natural and designed nanosystems starts from the design of instruments to visualize the invisible. It highlights the role of hands-on experience and toy models to foster productive scientific thinking and to embody abstract ideas. The models support students to uncover general ideas or universal concepts by theoretical reflections that generalize and abstract from the specific system. In order to foster these higher order processes, the theoretical embedding of the experiments and suitable instructional support is essential. Only cursory information on the conceptual background could be given in the present article. It is up to the educator and the teaching context to provide an adequate environment that elicits prior knowledge of the students and assists learners in conceptual reorganization and development.

The underlying experience-based teaching concept complements the theory-driven, axiomatic, deductive approach. As it strongly depends on analogical reasoning it is adequate, in concluding, to reflect upon the indispensable role of analogies and analogical reasoning for promoting new knowledge. Educators often have an ambivalent relationship and consider analogies a two-sided sword. Bunge (1973) [43] condensed the skeptic view into a catchy phrase: "In short, analogy is undoubtedly prolific, but it gives birth to as many monsters as healthy babies". While the negative side holds true for quick intuitive arguments as well as the superficial use of analogies, we have to give justice to their productive power and their indispensable role in human thought processes. In the traditional view prevailing in education, analogies elucidate one domain in terms of another [44]. Psychological theories describe analogy building as a mapping between source and target domain. Essentially, this is considered a one-way process: The base domain provides a model for the target domain [45]. The mapping is considered to operate on sets of explicit roles similar to the formal steps in deductive and propositional reasoning [46]. This algorithmic view is somewhat distant from the actual practice of creating and using meaningful analogies in science and, from my own experience, it is too restrictive to be fully productive for educational purposes. It neglects the non-decodable productive elements and creative leaps (cf. figure 1) in deploying, evaluating, reshaping and refining analogies and models.

Beyond one-way mapping there is a more symmetric relation between base and target domain. Similarities and analogies let the ideas flow back and forth. Learning tries out, discards und reinforces links in both directions. Analogy making elucidates not only concepts and functional principles within the target domain. It can act back and provide a deeper insight into the base domain as well (cf. the mutual reinforcement between principles of near field imaging and hearing in the preceding chapters). An essential part of successful analogical reasoning is to evaluate why and to which extent the analogy works. The reflective part is often neglected in teaching, but exactly this type of inquiry promotes knowledge by reinforcing generalizations and abstractions. In general, the analysis will reveal that the basic domain must embody relevant structural and dynamical aspects of the target domain in order to provide a successful model. Well-founded analogies are based on structure principles and dynamical processes of similar complexity in both domains. Lower complexity analogies have less explanatory power and can lead into a dead end.

Often, powerful models carry kind of a surplus meaning that goes beyond their original embedding, providing largely unexpected insights into new fields. As an example, the toy model of folding and unfolding resonates with a variety of abstract ideas from different science domains that by far transcend the original mechanical context. It even echoes with theories of the mind. For instance, the model of packing and unpacking genetic information shows similarities with the model of conceptual chunking, describing processes of condensing and unfolding information in our working memory (Figure 2). Is this an instance of superficial similarity, a mere agreement of metaphorical language, or a clue to a deeper connection? In fact, from a systemic perspective, the apparent similarities between genetic and cognitive processes can be ascribed to the interlinking of sequential and parallel mechanisms that also depend on design constraints of the information processing substrate. In genetics, information is stored sequentially in the base sequences of DNA. Unfolding small sections allows the transcription machinery to access different chunks of information in a parallel way. So, folding and unfolding solves the bottleneck of information access, presented by the sequential nature of the code. In this case unfolding describes structural transformations. In cognitive processing, the limited capacity of the working memory is the bottleneck. Only a small number of information chunks are available in parallel. Mental modeling unfolds the information content of the individual chunks iteratively by including more layers of meaning in sequential processes. In this case, unfolding has dynamical connotations.

This parallelism between mechanical folding and the unfolding of genetic and cognitive processes elucidates some aspects of surplus meaning inherent in powerful models. However, it is hardly possible to fully formalize this elusive feature of creative modeling. One can surmise that it is related to universality. In a weak sense, universality shows up in emergent processes, which can show similar patterns of evolution in completely different domains of experience. This allows tentative transfer of knowledge. As a strong principle, universality can be formalized for the context of phase transitions or in the universal behavior of dynamical systems at critical points. New types of behavior emerge and follow generic patterns as a function of order parameters. In fact, the unfolding of mechanical forms in the twisted rubber band falls into that category of critical behavior and emergence, for which an elaborated theory is available.

The transfer of experience from one domain to another, imperfect as it may be at the outset, facilitates a progression of knowledge in the course of modeling and theory refinement. We conclude with a quote from Einstein, who was a master of combining physical intuition with creating revolutionary theories that changed our views of the world. He characterizes the creative role of analogies as follows [47]: "It has often happened in physics that an essential advance was achieved by carrying out a consistent analogy between apparently unrelated phenomena. … The development of the mechanical and field views gives many examples of this kind. The association of solved problems with those unsolved may throw new light on our difficulties by suggesting new ideas. It is easy to find a superficial analogy which really expresses nothing. But to discover some essential common features, hidden beneath a surface of external differences, to form, on this basis, a new successful theory, is important creative work."

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