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The Mechanics of Creative Cognition: Orchestrating the Productive Interplay of Procedural and Conceptual Knowledge in STEM Education

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As a reaction to the growing economical, ecological and societal demands on education innumerous efforts and programs have been initiated throughout the educational chain to improve the quality of teaching and learning in the STEM field. On that background we sketch a framework to foster creative engagement in learning to promote scientific inquiry and modeling processes. In the theoretical part the article presents a dualistic perspective on the grounding of creative cognition in concrete experience, highlighting the productive and reflexive interplay of procedural and conceptual knowing. Their entanglement is pivotal to successful knowledge construction and application in science and technology. The 'mechanics' of creativity is elaborated exemplarily in a project based learning sequence that starts from investigating and modeling elastic forces as a basic paradigm of creative model construction. The creative part refers to conceptual expansions of the elastic spring model that assist in modeling emergent mechanical properties in hard and soft condensed matter. With additional moderate instructional input this knowledge is productive in creating basic models of the self-organized dynamics of biomolecular systems that orchestrate life at the cellular level. The sequence demonstrates how the interplay of hands-on experience and conceptual modeling can promote near and far transfer.

Keywords: Science education; STEM literacy; experience-based learning; creativity; modeling; analogical reasoning; embodied cognition; self-organization; nano-mechanics.

1. Teaching for Excellence and Creativity in STEM Subjects: A Global Challenge

A successful economic, ecological, social and cultural development in our societies largely depends upon our abilities to bring about scientific and technological innovations, which are substantial as well as sustainable. New technologies of engineering matter, energy and information emerge. The resulting products deeply transform the workplace and change our lives. The innovation rate and the global effects supersede by far the impact of earlier technological revolutions. The education systems are challenged to keep pace with the rapid and still accelerating evolution. As many international large-scale surveys have shown, the level of scientific and technological literacy is low and calls for substantial improvement. This applies not only to developing nations but also to the more developed industrial countries. As a reaction, in the recent past, we could witness an increasing political interest in science education. It resulted in various programs and initiatives all along the educational chain to raise interest in STEM subjects, to improve the quality science learning, and to encourage young people to take up a career in science and technology-related fields (Nat.Acad., 2019) [1]. Their common guiding line is to rethink and reorganize the ways we learn about science and technology in more authentic ways, using activating methods that encourage engagement and promote more comprehensive understandings.

Many STEM-subjects are considered 'hard' by learners. Especially, this refers to physics, mathematics and closely related disciplines from engineering. Students use evading strategies to circumvent the hard parts in order to minimize their learning effort. The missed learning opportunities impede the potentials of lifelong learning and degrade the quality of public understanding. The latter rests on the ideal of knowledgeable, responsible and mature citizens who are able to make sense of the natural and man-made world. Apart from open-mindedness, this includes the will to critically assess the opportunities and risks of new technologies as a basis of rational and informed decision making. Participation strongly depends on motivation and on sufficient scientific and technological background knowledge. The danger is more than hypothetical that ignorance and knowledge deficits misguide technological decisions towards a sustainable future. The need for improvement of scientific and technological literacy not only refers to the public in general. Even more important, it includes political and legal stakeholders, as well as the medial communicators as influencers of public opinion. In these days of fake news, misinformation, and questionable political rationality scientific knowledge and science-based evidence play a vital role for addressing societal and global challenges that we encounter at present and that we have to solve for the generations to come. Scientific and technological literacy along with social competencies and public engagement are crucial factors in making societies more resilient against economical and ecological crises.

Instructional approaches broadly classified as inquiry based are met with high expectations to raise interest in the STEM subjects and to improve the quality of learning [2]. However, there are indications that inquiry teaching can result in lower performance. In part, this can be attributed to substantial variations in the understanding of inquiry methods and their implementation due to traditions and boundary conditions of the educational system. Additionally, domain-specific patterns show up [3, 4]. A reanalysis of data from large scale assessments [5] confirms the convinctions of experienced educators: an intelligent balance of openness and guidance is important [6, 7]. Open and largely unguided inquiry is less efficient, as is strongly guided inquiry, known for instance from cookbook-type teaching labs. Improvements require ongoing educational efforts and strategies to promote higher order competencies such as complex problem solving, critical thinking as well as communicative and evaluative skills.

In a series of two papers, we present exemplary approaches to promote productive engagement in STEM subjects. In spite of the somewhat elitist connotation of raising creativity and the imaginative powers of students, this orientation is considered beneficial not only for top performers but also for average students as increasing evidence shows. The introductory part gives a theoretical synopsis on scientific inquiry, focusing on the reflective interplay of procedural and conceptual knowledge which is considered essential to self-regulated learning of science concepts and the development of fluid knowledge. The practical part presents exemplary ways of enhancing creative modeling by using simple hands-on tools as epistemic mediators to promote insight and knowledge transfer to more distant domains. In a follow up paper, the approach is extended to more comprehensive encounters with the cross-cutting concept of self-organization. This thematic and conceptual framework impacts on many STEM domains and presents a blueprint for modeling emergent structures and complex functions in natural and technological systems. Moreover, in a self-referential fashion, it provides us with fresh perspectives to reflect our own creative processes. The framework of self-organization refers back to the first part on self-regulated learning and the hands-on modeling of self-structuring mechanical systems.

2. Creativity and the Progression of Knowledge: Operationalizing Productive Cycles of Knowing in Science and Technology

Scientific literacy focuses on the necessity to provide largely authentic views on the methods of science and its role for society [8]. The related nature of science-framework explicitly addresses the creative and imaginative nature of scientific knowledge [9]. However, in the actual practice of school science, creativity largely remains a blind spot. Quite often, science and mathematics subjects are taught as the challenge to come to terms with a set of well-defined concepts, laws and theorems that hold the ultimate truth. In this tradition, the context of educational reconstruction and logical justification outweighs the context of discovery and its potential to enhance motivation and engagement of students. As a result, a severe image problem comes up. While doing science is strongly dependent upon the curiosity and the creative play of its practitioners, only few creative moments are experienced in learning STEM subjects at school. Moreover, the focus on conveying secure knowledge neglects a further challenge: Most of the issues at the interface of science technology and society that we encounter today are complex, ill-defined and defy simplistic approaches.

The neglect of creativity in educational mainstream can be partly attributed to its elusive character that evades a straightforward implementation. Additionally, the paradigm of a domain-general creativity prevailed in psychological theories [10]. The lack of crucial domain specific elements limited their impact on science education. In order to develop implications for science teaching it is helpful to approach creativity from different perspectives by amalgamating views from philosophy, epistemology and cognitive science with the specific demands of the subject domains.

In philosophy and epistemology, the understanding of what makes up a successful scientific theory has changed over time [11]. According to the long prevailing syntactic view of theories, a theory is formulated as a set of axioms in a largely formal language. This 'received view' was superseded by the alternative semantic view of theories, which considers theory as a collection of models. In both approaches the role of irreducible creative elements must be addressed. In the received view, they refer primarily to the ways how to arrive at axioms that make up the theory. In the semantic view, the creative moments are shifted towards the modeling process. Models are crucial for the acquisition and the unfolding of scientific knowledge. In order to be productive, models must represent essential structural or functional features of the target system. Conversely, for considering what is relevant and essential, the recourse to a theoretical perspective is inevitable. This inherent circularity demonstrates the complementary character of both modes of reasoning and knowing.

- The declarative mode proceeds in a logical, analytical and axiomatic manner based on definitions, rules and structures.
- The procedural mode proceeds in a largely analogical way by expanding on experience-based knowledge and practices.

Both modes have to be deployed in scientific reasoning. Moreover, their interdependence has to be addressed adequately in educational reconstruction and design.

Einstein's early view of scientific theory construction elaborates the relation between theory and experience at least in a unidirectional manner. He framed the role of creative insight in his EJASE model [12]. It connects the level of experience (E) with the level of axioms (A) and the propositions or theoretical statements (S) to be concluded from the axioms. While the conclusions S can be derived in a fully formal and logical way from the axioms, there is no such formal procedure in deducing axioms from experience. There are inherent irreducible creative elements depicted by the 'J' for jump or creative leap. With an adequate inclusion of the modeling perspective, the EJASE scheme can be generalized towards a generative scheme that applies to inquiry in science as well as design in technical disciplines. There are many ideas on the nature of inquiry and design processes. Most conceptions agree upon their cyclic character that iteratively link two different worlds, the world of experience and the world of ideas and theories.

The cycle of modeling and theory development requires a clear distinction between these two worlds separated by an epistemic cut (Fig. 1). Creative processes, which evade a complete logic or algorithmic description, bridge the epistemic cut. Different from Einstein's early unidirectional cycle, the creative linking works in both directions: bottom up and top down. In the upward direction, the creativity of a theoretical mind is in the foreground, while in the downward direction, a more practical mind is required to design ways how to intervene with the world. This view on creativity is democratic. It considers experimental, instrumental and design creativity on par with creativity in theorizing and generalizing, e.g., in seeing regularities, patterns, structures symmetries and invariants. In spite

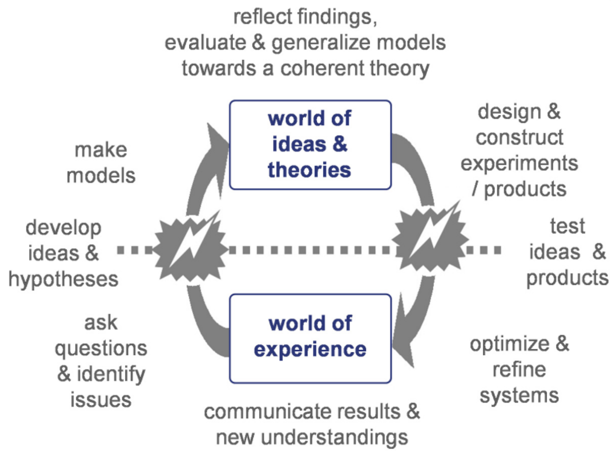

Fig. 1. Cyclic model of inquiry and design processes in science and engineering linking the world of experience and the world of ideas. Creative processes bridge the cut in both directions.

of the non-deductive or even seemingly irrational character of creative elements, the complete process is rational, based on the cyclic interweaving of generative and evaluative components.

Many instructional models have been put forward which are more or less refined versions of this basic cycle. In particular, the elaborated 7E learning cycle model is highly suited for practical implementation [13]. It addresses 7 phases, all characterized in a catchy way by processes beginning with an 'E'. They start from eliciting prior understandings as part of engaging in a problem, exploring the problem, phenomena or systems, explaining the findings through modeling and theorizing, evaluating, elaborating, and extending and generalizing the resulting conclusions. The latter phases are essential to the application and the transfer of knowledge. In science, this somewhat idealized view corresponds to the cycle of modeling and experimenting that starts from observing structures, patterns, regularities or anomalies, wondering, asking questions, initiating ideas or hypotheses and identifying ways how to create solutions and test predictions by designing and performing experiments. The initial ideas are successively refined into schemas, rules, principles, axioms and laws, finally condensed into a coherent theory. The corresponding processes in the technological design cycle refer to the development and evaluation of design ideas, to constructing, testing, trouble shooting, and optimization.

STEM teaching faces the challenge to strengthen the links between science and technology, without mixing their different goals:

- Science aims at generating fundamental knowledge about the natural and man-made world. Striving for a comprehensive understanding of our universe can be considered the motor of research.
- Technology aims at inventing and designing objects and systems that solve real world problems. The desire to create, build and implement can be considered the motor of technology. The compliance with established design criteria represents an important constraint.

In spite of the difference in aims and specific methods there are strong interdependences between scientific and technological progress. Both depend on creative minds that are able to link advances on the abstract, conceptual level with innovations on the concrete technological and instrumental level. Scientific research is dependent on technological tools and systems that enhance the human abilities to interact with the world. Conversely, technological processes of design and optimization are dependent upon knowledge from science, mathematics and the societal embedding. The interaction goes both ways. Scientific knowledge is implemented in new technologies. In turn, technological advancements enable or stimulate new scientific developments by extending the experiential and application space afforded by new tools and instruments. In accordance with the dichotomy of conceptual and procedural methods of knowledge generation one can discriminate between two kinds of creative processes and scientific innovations, those driven by new tools and those driven by new concepts [14]. Apart from individual creativity in science and technology the collective organizational and cultural climate is of crucial importance for bringing about new ideas, concepts, solutions and products.

3. The Cogs of Creative Cognition: Orchestrating the Reflective Interplay of Conceptual and Procedural Knowledge

Einstein, the icon of physical intuition, imagination and creative insight insisted that scientific reasoning of experts is only a refinement of everyday reasoning [15]. The same applies to modeling in science and mathematics. In daily routine we deploy mental models in order to plan actions and to figure out their potential consequences. In a way, we do experiments in thought continually, an instance of ordinary more or less creative reasoning. Along the same line psychological investigations state the ubiquity of conceptual structures and processes involved in creative thought and the close links between mundane and scientific creativity [16]. Why then, in view of the communalities between everyday and scientific reasoning, is the refinement so difficult? Why, in spite of initial interest, many students have learning difficulties and finally even resign especially in learning physics?

Many problems of coming to terms with the notorious hard and abstract aspects of science can be traced back to the affordances and constraints of our cognitive system. Especially, the limitations of our working memory represent a bottleneck to engage more deeply in scientific reasoning. 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 the capacity limit, research has greatly elaborated the important role of working memories in education and learning [17]. Current models assume two modality specific storage systems apart from the central executive: the phonological loop and the visuospatial sketchpad [18]. Basically, the systems implement two different ways of information processing. The sequential mode operates similar to processing the consecutive chain of events in language and action. The parallel mode unfolds a more global and holistic perspective, related to visual and spatial information processing. Deploying these cognitive resources in the development of scientific reasoning requires further iterative refinements.

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 and depends on syntactic knowledge. It includes focusing on the characteristics of a phenomenon or a process, which are considered relevant on the basis of theoretical assumptions, leaving aside irrelevant or superficial features. The inward bound part of chunking depends on condensation processes that associate different properties and condense them to a conceptual entity. In the opposite direction, semantic knowledge is required to link theoretical concepts with structures and processes in the real world. This includes some kind of expanding, unpacking or dynamical unfolding. The outgoing part is largely procedural and experience based. Figure 2 schematically depicts the chunking process in terms of interweaving syntactic and semantic knowledge elements. Additionally, it addresses multiple cycles of reflection that evaluate, reorganize and expand the knowledge. The reflective instance is relevant for generating meaning and understanding. Pragmatic knowledge emerges from these reflective cycles, leading to a nested structure of properties that pertain to different levels of conceptualization. While the condensing and unfolding of entangled concepts is a common notion to experts it poses severe obstacles to novice learners.

The chunking model reiterates the dual characteristics of the syntactic and semantic views of scientific theories. It anchors the epistemological perspective within a cognitive framework and facilitates educational implications, respecting the entanglement of conceptual and procedural knowledge and their specific characteristics. Procedural knowledge is largely implicit and holistic including

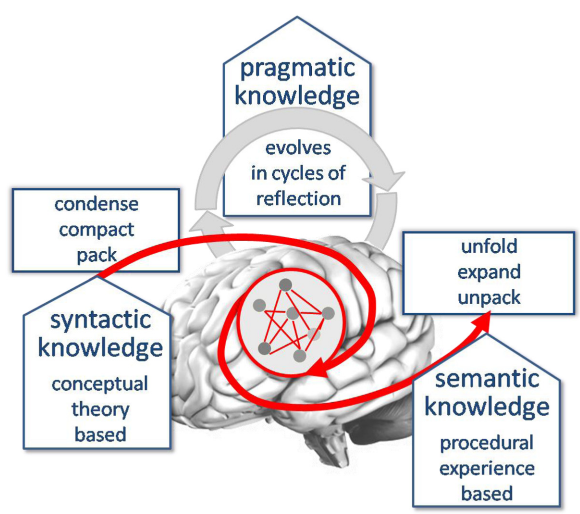

Fig. 2. Schematic dynamics of condensing and unfolding information chunks in relation to syntactic and semantic knowledge. Pragmatic knowledge emerges from multiple cycles of reflections.

visual and motor elements. It can be unfolded easily and in intuitive ways, circumventing explicit argumentation by chaining patterns of real or imagined actions. The much slower analytic, rational, theory-based mode serves as a complement and a corrective. 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 force-action schemata.

The easiness of the fast channel has a price. As experienced educators know and as examples from intuitive physics amply demonstrate: bare intuition is fallible [19]. It relies on perceptional biases and represents fragmentary aspects of reality. Although locally successful for dealing with common physical situations, intuitive knowledge cannot be generalized towards a coherent global picture. Unconstrained intuition severely restricts the learning potential of free, unguided inquiry as well as strongly guided cookbook experiments. In carrying out observations or experiments students tend to interpret the outcomes in terms of what they know or already surmise instead of adapting or reorganizing their knowledge to match the evidence. Primarily, they see what they already understand and much less reshape their knowledge in order to better understand what they see, as examples of intuitive concepts in primary education show [20]. Learners favor the more comfortable procedural mode at the expense of the analytic and reflective mode.

In spite of these deficiencies and shortcomings, creativity strongly depends on the intuitive, procedural mode of reasoning as kind of an 'intuition engine' that deploys efficient, yet only approximate, algorithms to arrive at rapid conclusions [21]. Intuitive strategies include thought experiments and deploy analogies; both are essential components of modeling and reasoning in science. Moreover, intuitive experience is necessary to ponder the relevance of ideas and to channel their development into productive directions. Thus, intuitive knowledge is an essential factor in making conceptual knowledge more productive for application and transfer. Metaphorically speaking, it lubricates the conceptual knowledge to become fluid knowledge. Experience-based knowing is essential for turning the often-prevailing rote learning of concepts and formulae into meaningful learning that leads to a deeper understanding. This includes approaching new problems by qualitative insightful reasoning before applying formal and quantitative tools.

A further aspect to consider refers to the use of tools that assist our limited perceptual and cognitive resources. On an instrumental level, suitable tools are required to interact with and to gain knowledge from the systems of interest. On the theoretical level, cognitive tools support modeling processes. Here the symbolic language of mathematics comes into play. It provides us with a wide variety of tools that assist in modeling the observed processes, regularities and structures, and in making quantitative predictions. In theory, mathematical tools reduce the cognitive load because they externalize parts of the modeling processes e.g., by suitable algorithmic or geometric routines. In practice however, 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 further constructs from processes and entities that relate them to the real world. The grounding of mathematics in concrete experience is often neglected or even deliberately suppressed in teaching. Only few renowned mathematicians have voiced their critique on the widespread formal scholastic tradition of teaching mathematics [22]. A theoretical recourse to the framework of embodied and grounded cognition is helpful in devising alternatives. To a large degree, the ways we think are shaped by the affordances and constraints of bodily experience. This includes mathematical thinking [23]. Grounded cognition elaborates the idea that symbolic operations are based in the brain's modal systems [24]. Cognition involves dynamical processes that link perceiving, acting and reflecting in agreement with the triad of processes in Fig. 3. Knowledge embodied in, or, linked to perceptual and motor states plays a major role in creating and unfolding mental models that simulate possible actions. Grounded cognition disentangles the generation of creative processes from their abstract and elusive character and shifts the focus towards more mechanistic, action-based models [25]. From that perspective, the role of experiments and practical hands-on experience for science learning has to be reconsidered.

Teaching for creativity requires intelligent ways of 'lubricating' the cogs of creative cognition by fostering relevant cognitive actions. From the foregoing theoretical synopsis, it appears essential to extend the 7E model by additional components in order to address and to orchestrate creative moments. As the extensions are intended to provide and to nurture creative seeds in the minds of students, they are much more difficult to boil down to concrete operations. In keeping consistency with the 7E model we formulate the upgrade in terms of respecting a similar number of 'I'- components and processes. First and foremost, as a synthesis of numerous meta-analyses shows, the inspiration by the teacher is the crucial factor for successful teaching and learning in schools [26]. The inspiration has conceptual as well as motivational and emotional moments. Admittedly, there is a tension in making individual creativity tangible to learners in the context of scientific problems where creative solutions already exist. Reproductive phases of learning are inevitable, but teachers, mindful of creative processes, enhance them by (re)-inventive phases by boosting the individual or collective creative acts of the learners.

Inspiring teachers and educational settings provide an adequate framework to initiate creative processes by stimulating imagery, imagination intuition and inventiveness. Moreover, teachers play an essential role in promoting instrumental creativity, assisting students the intelligent use of tools (e.g., for designing experiments and models or creating simulations). Last but not least, introspection is crucial. As introspective reflections are not an automatism, assistance and scaffolding by the teacher is required to initiate reflective cycles. These cycles iteratively evaluate and generalize the findings and integrate the new insights into a coherent perspective. In order to strengthen their metacognitive abilities, students must become aware of the nature the important role of these processes to promote efficient self-directed learning in the long run. Beyond general strategies, this requires a clear focus on the specific conceptual and methodological challenges of the respective scientific domain. Accordingly, successful teaching and learning depends on a reflected orchestration of bottom-up and top-down methods, providing an intelligent balance between autonomous construction and inventiveness on the side of the learners, complemented by effective instruction on the side of the teachers. The balance depends on the complexity of the subject and on the degree of experience of the students. These general recommendations are in line with conclusions from meta-analyses on the benefits and shortcomings of discovery-based instruction [27]. For more detailed expositions of evidence based pedagogic approaches towards creative teaching and the development of the students' capacity and motivation for lifelong self-directed learning cf. [28, 29].

4. Hands-on Model Construction: Unfolding the Mechanics of Intuition, Invention and Creative Insight

The research line of creative cognition identifies conceptual combining and expanding as essential processes of generating new insights by adapting and transforming existing knowledge [16, 30]. Additionally, analogical transfer is utilized to explore the unknown and to tentatively expand and adapt knowledge in order to exploit new domains of experience. By analogy, the phenomenology of creative processes, based on combining, extending and transforming concepts, can be mapped perfectly to models of emergent complexity in mechanical systems. For that purpose, we use experience with common everyday objects to investigate self-organizing structural or dynamical transformations. Driven by changes of external parameters new forms and new functions can evolve in these models — a basic paradigm of emergence and creativity. Thus, the 'mechanics' of creativity, a somewhat unexpected or even provocative notion, can be made tangible and incorporated into our intuitive knowledge base by studying these transformations. Mechanical metamorphoses assist in transforming ideas and models.

The approach is elaborated exemplarily in the subsequent project-based learning sequence located as a cross-disciplinary project at the intersection of physics, material science and biology. It builds upon ideas from the pioneering research of Clement, [31] who investigated creative model construction in scientists and students. A main data source were investigations how both groups work on the spring problem, predicting the properties of elastic springs with different shapes. He finds similar forms of successful heuristics both in students and in experts. When confronted with an unfamiliar problem both groups initially use intuitive, non-formal reasoning before finally resorting to more formal arguments.

Thus, in educational design, it is more than plausible to provide sufficient space for experience based non-formal learning processes. In this spirit, we consider the strengthening of the students' creative modeling competence a key strategy towards promoting deeper conceptual understanding of complex scientific concepts.

The project is based on investigations of elastic forces in different material systems. The ensuing modeling processes require substantial extensions of the elastic spring model which include interlinking non-formal procedural with more formal conceptual approaches. We present an overview of the course and highlight representative qualitative findings. It addresses physics teacher students in their 5th semester. Two cohorts ($N = 8$ & $N = 10$) took part in 4 afternoon sessions each, with the students working in groups of two. The sequence starts with collecting ideas of designing, constructing and testing a computer-based extensometer to investigate the tensile behavior of materials. The final system uses readily available components such as a graphics tablet and a strain gauge attached to an elastic beam for recording the tensile force and the extension. Its pedagogical charm lies in refining our intuitive force-action schema by combining the subjective feeling of force with an objective measurement and a graphical display of force-extension curves [32].

4.1. *Exploring elastic forces in everyday materials: From the spring model to substantial conceptual transformations*

The first session was mainly technology oriented to study construction principles of commercial extensometers, to devise a simple, robust design and to construct and test the final system (Fig. 3). In the second session the initial tests were refined by systematic measurements of the tensile behavior of strings and wires made up from different materials. A comparison of the results reveals basically two different types of force extension curves. Metals show a steep initial linear increase before the curve flattens and the wire finally breaks. Polymer materials behave differently. They are much softer and by far more extensible before finally tearing. For brevity we omit further refinements of the investigations and discussions that refer to extension-contraction cycles and the breaking behavior. Instead, we focus on the essence of the models that the students brought up in order to explain the collective nature of elasticity, emerging from the interaction of an ensemble of atoms or molecules.

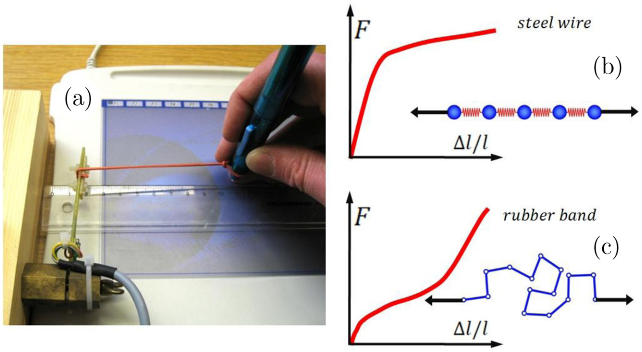

Fig. 3. (a) Design of the hands-on extensometer. Typical force-extension curves of a metal wire and a rubber band with iconic representations of relevant basic models, i.e., the elastic spring model for crystalline solids (b) and the freely jointed model for entropy elasticity of polymers (c).

In the metal wire case, all students were able to reduce the observed behavior to the action of attracting and repelling interatomic forces holding the atoms in regularly arranged equilibrium positions. In accordance with textbook knowledge, most students applied the elastic spring model and visualized these forces with tiny springs that mimic compression and expansion of the solid body (Fig. 3(b)). They correctly addressed the energetic aspects of small deformations that stretch or compress the springs reversibly. The work performed by stretching can be regained by reversing the process. Thus, their modeling captured the essence energy-based elasticity. However, this explanatory pattern is insufficient to understand the behavior of elastomers such as rubber. These highly elastic substances consist of long polymer chains which are cross-linked to form a random network. As the physics students lacked sufficient knowledge on the chemical structure, they were unable to arrive at conclusive explanatory ideas.

As a conceptual preparation for the next sessions students were asked to obtain information on the chemical structure and the resulting properties of polymers with a focus on rubber elasticity and to prepare a presentation of their findings, based on internet resources (preferably Wikipedia articles) or textbooks of their choice. Additionally, as a conceptual grounding for further applications and elaboration of the models, they were recommended to refresh and align their background knowledge on the structure and properties of biologically relevant polymers such as proteins and DNA.

4.2. *Creative twists and shape transformations: Hands-on modeling life's nanomechanical secrets*

In the third session the models of polymer elasticity from the students' research were presented and discussed, in order to condense the models to their conceptual essence. With moderate instructional input and focusing, this finally resulted in the freely jointed model shown in Fig. 3(c). A single polymer chain is represented by rigid segments that rotate freely at flexible joints. The chain molecule can occupy innumerable configurations of practically equal energy which change continually due to thermal motion. The most probable state has maximum disorder (high entropy state). Stretching the chains diminishes their configuration entropy. The restoring force is driven by the tendency of entropy always to increase. This is a highly idealized basic model of entropy elasticity. Notably, no force is required for changing the rotation angle at the joints.

As the students' ideas still strongly adhered to the basically static model of spring elasticity, they had initial difficulties in fully appreciating this dynamic concept of elastic behavior. They were asked to explain the thermal effects of elastic deformations that can be observed by using their lips as thermal sensors. The band heats up by stretching and cools upon retraction. Only four students were able to correctly explain the findings and link them to entropic processes. In spite of these limitations the basic idea of the chain model was applied successfully to interpret pulling experiments with individual protein molecules from more recent research.

As an input to challenge the students' ideas, results from force-extension measurements on Titin molecules were presented [33]. This research is carried out by atomic force spectroscopy, using the deformation of a tiny micro-fabricated elastic beam to study the mechanical properties of nanometer-sized molecular structures. The measuring principle of extending a protein string attached between the fine tip at the beam's end and a substrate is fully

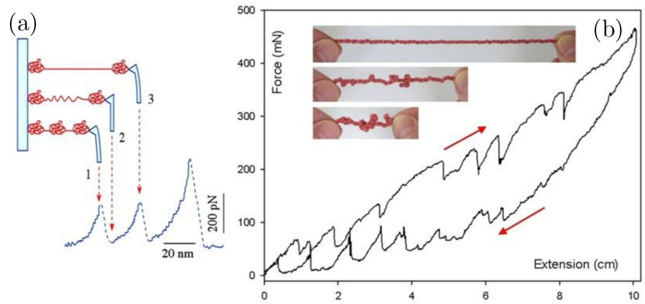

Fig. 4. (a) Atomic force spectroscopy measurements on Titin molecules. (b) Force-extension curves of a twisted rubber band. Arrows indicate the direction of the extension-contraction cycle.

analogous to the above extensometer system. Titin is a 'giant' muscle protein made up from a sequence of protein string repeats that are folded to a periodic chain of globular structures. Upon extension the pulling force varies in a saw-tooth pattern (Fig. 4(a)). The number of force spikes corresponds to the number globular domains involved. This behavior totally defies our naïve force action scheme. Although the molecule is extended further, the force repeatedly drops to near zero.

With the above highly reduced basic model of entropic elasticity the students had no problem in explaining this seemingly counterintuitive behavior. Entropic forces resist the untangling of globular domains. As soon as the critical force is reached a single domain unfolds. Once unraveled, the force drops and only increases when another domain is stretched. This pattern repeats until the protein is fully straightened. On a functional level, the students were able to address the biological benefit of this scheme to resist mechanical overload. A series of many entropy springs absorbs force peaks and prevents the chain molecule from tearing.

When confronted with the challenge to devise tangible models of protein folding, several students brought up the idea of twisting a rubber band. The tangles that occur as a result of twisting get untangled when the band is stretched. The tangles reappear in a reproducible way upon slowly relaxing the tension. Force-extension measurements on the tangled system confirm that every act of entangling or disentangling a twisted domain is connected with a spike in the force graph [34]. The resulting saw-tooth pattern resembles the graphs of protein pulling experiments (Fig. 3(b)). A complete deformation cycle produces a hysteresis in the force-extension graph, an indication of irreversible processes that dissipate energy. On a metaphoric level this model breaks down the unfolding of complexity to its linguistic origins: the Latin root 'complicare' means to fold.

As an indication of successful modeling, most students were able to formulate the limitation of this simple static model of structural transformations. As it only includes the unfolding of structural complexity, it lacks the dynamic part of entropic disorder. Moreover, beyond describing the obvious superficial similarities, they were able to formulate the analogies to protein folding in a more detailed way and to consider the folding process from an informational perspective. At critical tensions, the one-dimensional twisted band folds into a three-dimensional object. Due to material imperfections in the band, the emerging kinks appear reproducibly in a seemingly preordained manner. This is comparable to shaping the functional 3D protein structure, which is latently present in the linear chain, encoded in the linear sequence of the amino-acids. In the subsequent plenary session, the links between protein form and function were addressed. Students discussed various functions of proteins and presented representative structural and functional models from internet resources. The examples elucidate principles of complex program-driven and environment dependent molecular self-organization processes that underlie life's productive biomolecular machinery, orchestrating the exchange of matter, energy and information.

For brevity we omit a detailed description of the fourth unit that focused on geometric and topological properties of transforming elastic strings to loops and coiled structures. Via analogical transfer the models promote a basic understanding of the hierarchical structuring of DNA-strings into coils and supercoils. The condensation and unfolding of these structures underlies the transfer and the regulation of genetic and epigenetic information. Once again, as in the foregoing protein folding example, the rubber band as a toy model triggers relevant ideas on the role of mechanical self-organization, in the broader context of self-sustaining biological system dynamics.

5. Benefits of Creative Modeling: Qualitative and Quantitative Findings

In a concluding retrospective the students were asked to discuss their leaning experience. After that each group wrote down their own views. Table 1 presents representative quotes. To begin with the critical aspects, the students, arguing on the basis of practical school experience from their internships, addressed difficulties of implementing similar hands-on projects within the traditional curricula. They see main obstacles in narrow time constraints and in the interdisciplinary nature of the approach. As in most German syllabi the individual STEM-subjects are taught separately, they consider project weeks or out-of school leaning sites as viable alternatives to enrich the prevailing more formal teaching.

Table 1. A selection of teacher students' comments on their project experience (my translation).

- The design of the measuring system without expensive equipment was interesting. I will try out similar projects with computer tools and sensors later in my own teaching.
- Preparing such a project is very time consuming and increases the workload of a teacher, but I think the effects on the students' motivation and learning can be great.
- I had no clear ideas about protein folding but the project helped me to better understand this fascinating topic.
- It came to me as a surprise to see how important ideas from mechanics are important in understanding biological processes. Even genetics depends somehow on mechanics.
- I found it extremely useful to apply physics knowledge to practical problems and to better understand the properties of materials that are important in technology.
- The experiments were fun. Some required thinking out of the box (literal translation: to look beyond the rim of the plate). The project was interesting as it linked physics with chemistry and biology.

Beyond that, the comments were positive, especially with respect to linking physics with biology. Some participants were even more even enthusiastic mentioning the encouragement that they felt by devising, testing and applying tools to carry out investigations and to gain new knowledge. The project, they argued, gave incentives for devising similar educational settings in their own future teaching. Especially the idea of complementing the traditional formal approach to mechanical concepts by practical experience was described extremely helpful to discover the physics behind the properties of everyday materials. The reactions give a clear indication that the students experienced and valued the transfer of their learning. The extensions of the mechanical models and the transfer towards basic insights into aspects of biological self-organization were considered demanding but also rewarding. Four students mentioned correspondingly that this helped them to see the essence and the core ideas of the processes amidst a host of biochemical details.

While these qualitative results refer to a small group of advanced physics teacher students, similar approaches to modeling the structure and function of DNA were recently investigated on the classroom level by using detailed tests of the resulting model understanding. Grade 9 students took part in a one-day activity in an outreach lab on genetics that included hands-on experiments and a modeling section to construct DNA models. The findings confirm that combining hands-on experimentation with model-based tasks is successful in promoting students' understanding of scientific models [35]. Two different strategies based on active modeling versus passive model viewing and discussing the models were also compared. Both student-centered approaches positively affect the students' understanding of models. The findings confirm that low achievers particularly benefitted from the modeling practice [36]. This is in line with the introductory claim that promoting scientific creativity via modeling is beneficial not only for top performers but also for average students. The observed discrepancies in the impact of both approaches in terms of retention and gender effects require further clarification [37].

6. Outlook: Tuning up the Intuition Engine by Exploiting the Surplus Meaning of Powerful Models

In retrospect, the present theoretical framework highlighted the dynamics of creative processes in science. It elaborated their grounding in different modalities of our cognitive system and focused on optimizing the interplay of bottom up and top-down processes by theoretical reflections that create and refine scientific concepts. Explorations and transformations of concrete models played a major role in that approach. These highly reduced 'toy models' can be considered cognitive tools that ease the conceptual handling of more demanding theoretical concepts. In spite of their apparent simplicity, they open up unexpected views upon emergent complexity in a wide range of systems. In encounters with a prepared mind, they inspire insights that transcend the original mechanical context of their initiation. The systems embody ways of thinking by doing. They represent epistemic mediators to create new ideas to approach more abstract concepts.

From a theoretical perspective the power of hands-on modeling fits into recent findings on physical scene understanding and its computational underpinning. Research proposes a cognitive mechanism that provides us with a flexible interface, connecting both lower-level perceptual-motor systems and higher-level cognitive systems. This 'intuitive physics engine' uses approximate probabilistic simulations to make rapid physical inferences in everyday situations [21]. The judgments are rather robust when dealing with familiar systems (e.g. predicting the toppling of a stack of objects or the strength of an elastic rod). However, they are only partly successful in dealing with more complex situations such as the shape transformations of elastic strings in the above examples. A full understanding of inherent topologic and energetic details of the structuring can become extremely demanding. The toy systems demonstrate that hands-on and playful exploration in connection with more systematic and formal reflections can gradually enhance the powers of intuition to deal with new and more complicated situations, leading to extending and reorganizing the conceptual repertoire.

Another aspect of creative modeling requires closer consideration. It refers to the scope of specific models that we promote in teaching. As educators we have to value the contribution each individual student. On the other hand, we have to acknowledge that some models are more productive than others. This calls for adequate assistance in guiding the students' intuitions accordingly. Often, powerful models carry kind of a surplus meaning. They illuminate beyond the original domain, for which they were devised. By this, they facilitate the transfer of learning to more distant domains. From a conceptual point of view this seemingly elusive feature is linked to more comprehensive or even universal characteristics which are embodied by the models. Quite often, these latent powers are hidden to the initial perspective of the modeler. Models must unfold sufficient complexity and include relevant structural or functional principles to be successful in the long run.

This also applies to the above toy models, whose function incorporates more general nonlinear processes. Their creative transformations, embedded in different contexts, inspire preliminary Inklings of self-organization and its powers to drive evolutionary processes in inanimate as well as in living systems. The dynamical perspective on emergent processes and their comprehensive role in many STEM subjects is developed further in a follow-up article [38]. Again, it uses hands-on experience to provide creative encounters with the cross-cutting concept of self-organization by devising and exploring models. Theories of self-organization describe how patterns, structures and new types of behavior emerge in energetically open systems, resulting from the local interaction of many components. As an external control instance is missing, the underlying philosophy is counterintuitive to our habits of causal thinking. This calls for comprehensive educational approaches that unfold the productive potential of this concept in many domains of experience, including, in a sense, the physics of the mind.

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