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# Interdisciplinary nature of nanoscience - implications for education

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A lot of expectations rest on the interdisciplinarity of nanoscience, and it has even been proposed as the deciding factor in the progress of the field [1]. What opportunities and challenges does the interdisciplinary nature of nanoscience bring to science education at different levels? This chapter first analyzes the much-discussed interdisciplinarity of nanoscience today, and then discusses how and why those features should be addressed in education.

## 1. Introduction

### 1.1. Definitions of Interdisciplinarity

Interdisciplinarity has been loosely defined as activities that combine, apply or integrate two or more disciplines. The field can be further categorized according to the degree of disciplinary integration, the types of practices involved, or the rationales [2]. As an example from the first category, interdisciplinarity can be contrasted with *multidisciplinarity*, which is much more common. Multidisciplinary work juxtaposes the participating disciplines, it is additive instead of integrative [3]. Interdisciplinarity, on the contrary, requires stronger ties, overlap and integration of various disciplinary perspectives. Other regularly used terms are cross-disciplinarity, which does not require active interaction or integration of different fields - and transdisciplinarity, which goes beyond interdisciplinarity in merging traditional disciplines and dissolving disciplinary boundaries. Today, transdisciplinarity is used almost interchangeably with interdisciplinarity, as its goals are embraced by many interdisciplinarians [4].

The disciplines represent several things: storage of relevant knowledge, a system for producing said knowledge, and the people drawing from such knowledge, based on certain methods, interests, standards, and traditions [5]. The development of the discipline as a social institution with closed membership, journals, societies, and job openings - all beneficial developments for the scientist! - and the perceived competition from scientific research institutes has shifted the University from education- to research-oriented [6,7].

The drive for interdisciplinary research can result from the needs to tackle a multi-faceted, complex problem [8--10] that cannot be addressed by a single discipline. Krohn [11] describes all interdisciplinary ventures as tackling problems that include the real-world complexities, whereas a mono-disciplinary approach theorizes and simplifies the complexities away. This is the perspective of interdisciplinarity applied at the demands of a problem.

On the other hand, it can arise from a shared interest in an object of study, or pressing social concerns and demands that do not fit within a single disciplinary frame – such is the case, e.g., in environmental

research. Such shared interest and a will to see if there is more to a question than meets the eye can be the starting point to creative collaboration and discovery [12]. This perspective recognizes that people may be inherently interested in seeking integrated views and new perspectives or applications. Jacobs [13] lists other reasons for interdisciplinary research; they include validation of results by other disciplines, overlapping claims to intellectual terrains, and the mundane lure of funding available in solving contemporary problems.

Finally, the complete picture of interdisciplinarity comprises both *cognitive* and *socio-psychological* elements; the discipline as a body and production methodology of knowledge, and the social body of the disciplinary knowers and their socio-cultural dynamics. Both of these elements are crucial to enabling and understanding interdisciplinary research [14,15].

### **1.2. The Disciplines Contributing to Nanoscience**

The Royal Society and The Royal Academy of Engineering [16] define nanoscience as “the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.” This definition does not bind nanoscience into any specific discipline, but leaves the research methods open. Nanoscience is open for interdisciplinary research of material samples at a specific scale. By nanoscience and technology (NST) we refer to utilization and application of nanoscience and -techniques in products.

Many fields of nanoscience clearly interlink two or more of the traditional disciplines, mostly physics, chemistry, biology, material science, medicine, and engineering. An example of such a field is research on steric effects of cell membranes, where chemists, biologists and physicists have overlapping research interests and approaches that complement each other, and the scientists from different fields come to share the same, novel instruments to observe the phenomena and probe the samples. When researchers from different origins take part in interdisciplinary projects, they have no shared common ground in their disciplinary expertise. It must lay elsewhere; suggestions include the objective of research, as well as the approaches, instrumentation and technology. While the nanoscale is shared, there are signs that it is viewed very differently by physicists, chemists, and biologists, each taking the point of view based on their disciplinary tradition and epistemology [17]. In addition to the different backgrounds and approaches, they can have different objectives. The local co-operation is motivated by the mutual interdependence: it helps different actors to reach their goals.

It is clear from a multitude of case studies that a minimum requirement for successful interdisciplinarity is that the participants learn to see the situation from the viewpoints of collaborators with different backgrounds [18]. This means that an interdisciplinarian has to develop a sufficient understanding of the nature of the relevant disciplines [7]; we discuss later what adequacy might be for nanoscience.

### **1.3. The People That Do Science**

James Watson, the co-discoverer of the double-helix structure of DNA molecule and a Nobel Prize of medicine winner in 1962 expressed the importance of collaboration as "Nothing new that is really interesting comes without collaboration." Social and psychological elements of interdisciplinarity are

revealed by numerous studies/writings focusing on the challenges to organize interdisciplinary research projects in the areas where the viewpoint would be new and interesting.

The challenges of interdisciplinarity relate to the difficulties of crossing historical disciplinary borders at universities, which have defined the ways of acting and thinking for hundreds of years, and also provided the foundation of institutions together with the careers and success in those [5,6]. The institutional structures, such as recognition and assessment of work, e.g., for tenure, are still lagging behind, rather than acknowledging interdisciplinary work as academic credit, and fully enabling scientists to build a career with interdisciplinary collaboration [19]. This is a heavy incentive for many researchers to stay in a field they were trained in, rather than build a new, interdisciplinary identity (see section 2.2.3).

The attraction of interdisciplinary work still works for many; it offers exploration, adventure, and possibility of collaboration with very different fields. Nanoscience has so far also been a field that offers funding possibilities (even security, in comparison with many less popular fields) - there is high government funding as well as research collaboration with companies. There are lots of expectations that it will have a big impact on industry and medical technology. It has the feeling of being a field on the rise, with ever-increasing numbers of citations and patents [20].

Whatever the reason people enter the field, they are still confronted by the institutional and social factors in doing nanoscience. While interdisciplinary science can be pursued solo, it is certainly often linked with teamwork and team science [21], particularly so in natural sciences. Getting collaboration and a community going with people with different disciplinary identities and habits has its own difficulties, which we will address in more detail in section 2.2.

#### **1.4. Why Consider Interdisciplinarity in the Context of Education?**

The concept of *discipline* has strong educational connotations, as it originates from the Latin for “teaching.” The disciplines in lower education are called “school subjects.” They can be thought of as university disciplines translated for use at schools, but the choice and content of school subjects is of course also a societal and political decision.

Interdisciplinarity has been a slogan of educational reforms at all levels: from interdisciplinary universities (in-depth discussion in [3]) to integrated school curricula. The advocates mainly argue that interdisciplinary science teaching supports students’ understanding of connections and relevance of concepts to other concepts and broader issues [22]. Indeed, many finer points of epistemology or synthesizing information will not do much to younger students, who are still working on their higher-level thinking skills. Currently an interdisciplinary strand in general education is included, e.g., in the Next Generation Science Standards (NGSS) as the cross-cutting concepts [23].

Repko [7] reflects on the knowledge intensity of working life. The future of industry and labor require persons who “understand, use, and integrate knowledge and methods as well as collaborate with disciplinary teams across industry sectors and cultures.” Jacobs [13] introduces product development as

today's interdisciplinary empire; his example is from making skin cream, where "a diverse team is needed, including basic scientists, clinicians, specialists with a background in managing clinical trials, financial analysts, and marketing specialists, among others." Such a diverse skillset will not be cultivated within any one faculty or technical college, be it chemistry, marketing, or dermatology.

We expect the skills of working and coping with information - "hard skills" - and people - "soft skills" - from different backgrounds and disciplines to be increasingly important for tomorrow's adults. They are relevant to everyone within our world of increasing diversity and multitude of cultures; many of the interdisciplinary soft skills are, indeed, the same as cultural competence [24].

Within a higher education perspective, Newell [25] makes a bold prediction that interdisciplinary undergraduate education will radically increase. At the moment, researchers that have received an NSE training all the way from the Master's or Bachelor's level, are not yet in positions of power in the academy. The long-established nanoscience Bachelor's or Master's programs have recently hit the ten-year mark, with University of Toronto's Nanoengineering program being the oldest, launched in 2001 [26]. The first in Finland are now working as postdoctoral researchers and senior lab managers, or in the case of Taiwan, some as junior professors [27]. We know that early interdisciplinary experiences, such as student research, predict future interdisciplinary research paths [28]. As a new generation of interdisciplinary-minded researchers reach positions of power, they will be more likely to promote interdisciplinary research and education, creating a positive feedback loop [25].

Simply predicting or watching over an increase in interdisciplinary education is not enough. There are social and psychological factors, which should be considered in the education of the future citizens, customers, workforce, and researchers, to avoid some of the current problems and pitfalls.

In what follows, we first elaborate on how interdisciplinarity appears and affects research in nanoscience. On the basis of that analysis, we discuss implications for interdisciplinary nanoscience education at general as well as academic levels.

## **2. Interdisciplinarity in Nanoscience**

A lot of expectations rest on the notion of interdisciplinarity of nanoscience, and it has even been proposed as the deciding factor in the progress of nanoscience [29]. Stevens, Sutherland and Krajcik [30] see in it a promise of a significantly greater impact on society than previous leaps in scientific knowledge. Perhaps interdisciplinarity is the only thing that gives a name to nanoscience: after all, chemists, physicists, biochemists and cell biologists have been studying phenomena at the nanoscale – the dimension of atoms and molecules – for centuries (see e.g., [31]).

There can be various degrees of interdisciplinarity in scientific research. NST has been referred to in terms of reductionism of the natural sciences (see [32]); i.e. the scientific ambition is not only to *link* quantum mechanics, solid-state physics, inorganic chemistry and molecular biology, but to *unify* them as well – at least partially, in the nanoscale. Some scholars have gone even further, suggesting that

nanoscience prepares the way for a greater convergence of sciences, the so-called nano-bio-info-cogno-, or *NBIC* (Nanotechnology, Biotechnology, Information Technology and Cognitive Technology) – *convergence* [1,33,34]. As Schummer [15] puts it, interdisciplinarity “can go as far as to either unify two or more disciplines or to create a new 'interdisciplinary' (hybrid) discipline at the interface of the mother disciplines.” However he sees no unification in the present, describing nanoscience research as “several auxiliary disciplines [that] are strongly associated with one major or also identified as a ‘mother’ discipline and researchers working in auxiliary disciplines make tremendous efforts to contribute to the major discipline”, similar to worker bees tending to their queen.

Both of these ideas - the melting pot, and the queen bee discipline fed by subordinate disciplines - have been used to describe NST, and we will address them again in contexts of bibliometry and published nanoscience research, as well as researchers’ disciplinary or professional identity.

While we are in no way against monodisciplinary research within nanoscience, in the following sub-chapters we explore how interdisciplinarity appears in researchers’ work. We seek to show that different degrees of interdisciplinarity do exist in nanoscience and give the reader an impression of what that interdisciplinarity brings to NST. We have a focus on work in groups or teams. We use this understanding later to discuss what kind of interdisciplinary training would help future scholars to adjust into an interdisciplinary research world, or help all citizens appreciate science - especially nanoscience - and society more fully.

In the following, we explore the cognitive and social sides of nanoscience including a few anecdotes from nanoscience research groups, from both interviews and self-edited stories [35--39]. A similar structured look at the Nature of Science has recently been made by Irzik and Nola [40,41] and Erduran and Dagher [42]; we share the same two big categories (cognitive-epistemic and social-institutional). Within the subcategories we have focused on the specifics of interdisciplinary science, and therefore some of the categories relevant to nature of science(s) in general are missing.

## **2.1. Nanoscience as a Cognitive-Epistemic System**

### ***2.1.1. Building an Adequacy in a Discipline***

The disciplinary adequacy, prerequisite knowledge, and basic observational categories mentioned in the previous chapters all fall under the umbrella of establishing a necessary amount of familiarity with the relevant disciplines. It does not mean knowing the “important findings” in a discipline as much as it involves an understanding of the allowed assumptions, preferred methods, standards for evidence - much of it unsaid, but tacitly understood by someone educated in the field [43].

In case of nanoscience, the relevant disciplines are usually known from the start of the research project, and aside from the beginning researcher, participants come to the table with a disciplinary adequacy rather than attaining it during a project (as described by [7], as part of the Interdisciplinary Research Process). The disciplinary knowledge base is of course extended as required during the project. In an interdisciplinary education this adequacy could be obtained already during a Bachelor’s degree.

With majority of nanoscience researchers still having a background in a monodisciplinary environment, beginning nanoscientists come to the table without a general understanding of the methods and typical assumptions used in each of the natural sciences. Not surprisingly, scientists typically spend little time thinking about the different methodology or epistemological assumptions of their neighboring disciplines. For some, it manifests as a resistance due to their strong disciplinary identities, and they minimize contact to other disciplines down to a superficial “borrowing of results [36].” Others begin the process of building adequacy to minimize the cognitive struggles at the edges of their disciplinary world.

One visible difference between disciplines is jargon, or the specific terminology. Professor Korppi-Tommola from the Nanoscience Center at University of Jyväskylä (NSC-JYU) acknowledges that it is a big barrier to overcome: “Patience and perseverance are needed. - Becoming acquainted with biology terms for example, takes time. It just doesn’t seem to stick without having read their 1000-page fundamentals textbook [39].” Once obtained, Chari [36], on pp. 111-114, highlights the ease with which people use jargon without noticing it. She shares an example of a physics background graduate, who described his frustration with other disciplines’ jargon, simultaneously using “acronyms and terminologies including UV (ultraviolet), AFM (Atomic Force Microscopy), LASER, TEM (Transmission Electron Microscopy), plasmon resonance, aliasing, diffraction pattern.” She notes that “[the graduate] probably assumed I had a physics background as I had met him earlier at a physics student conference.” Shared jargon becomes an intellectual shorthand in discussions, and creates a communality among those who share it.

In the social skills section we note that it’s important to be able to ask for clarification, and if the audience is known to not share the jargon base, to accommodate speech to a shared level. For a long-term collaboration, there simply is an amount of terminology to come to terms with, as a part of developing the disciplinary adequacy. Frequent interaction helps establish contact languages, systems of discourse that can vary from the most function-specific jargons, through semispecific pidgins, to full-fledged creoles rich enough to support activities as complex as poetry and metalinguistic reflection [44].

While there are countless examples of jargon inhibiting understanding (see examples of syno- and homonyms in natural disciplines in [36] p. 144), there’s more to disciplinary adequacy. Andersen [18] argues that interdisciplinary research involves epistemic dependence between researchers of different disciplines, sharing a conceptual understanding and mental models of the situation. The knowledge of the group as whole is non-utilizable, if the members are unable to share the conceptual structures, to varying degrees, determined by their understandings of each discipline involved. As is typical in nanoscience, graduate students often have supervisors from different disciplines. If an intellectual connection between the people doesn’t happen, as either the student, the supervisor, or both lack an adequacy in the other discipline, the connection is unlikely to be realized in research either.

Chari [36], on pp.128-130, describes a student “meeting his second supervisor only for the administrative updates of his project while his meetings with his first supervisor (from his discipline) were mainly to discuss research findings and seek suggestions. He favored the meetings with his first supervisor as they were targeted to discuss the inputs, suggestions and experimental challenges.” His other group members saw value in development of multiple types of coating, while his research was

about the optimization and parameters of the process of coating - typical to his disciplinary home. He experienced intellectual solitude because of the inadequate understanding of disciplinary perspectives both ways. In extremes, the solitude becomes a judgmental trench. Chari [36], on pp. 148-151, found that it's a very common experience amongst nanoscientists. Their research, performance, and actions being judged through the lens of another discipline becomes a form of criticism, as the judged actions, such as validation of results, do not necessarily conform to the traditions of the other discipline. To the student, the different expectations and goals for the research appeared as criticism of the value of his research.

Without recognition of the inadequate disciplinary understandings as the cause of this problem, one may simply become more entrenched within their home discipline. Prompts or hints about the wider context cannot remove these blinds; even the industry and faculty panelists in a Delphi study [45] rating relevant competencies in nanomanufacturing "did not rate some of the biology and chemistry competencies because they [were] not related to the respondents' background."

### ***2.1.2. Interdisciplinary thinking: Networks, syntheses, delicate adjustments?***

There are several studies on how an interdisciplinary understanding - that is, within an individual mind - is formed. The overarching theme is integrating distinct epistemologies, whether they be of research methods, targets, validation, or the choice between inductive and deductive reasoning. We overview theoretical models of interdisciplinary thinking and exemplify them in a research project in nanoscience.

Krohn's [11] idea of an interdisciplinary understanding in an area is a network of individual cases, within which the similarities and differences between cases are compared. The tension between understanding the specific details of a case or system, and searching for generalizable information – laws – demands new types of competencies. He emphasizes that it is not a search for "typical cases", but the individuality of each case be preserved. Situational assessment, a repertoire of strategies, and recalling components of the case network for comparison to previous solutions are the main skills to develop. The means are by observation of masters and most importantly, exercise of solving such cases. The fruitful and accurate description of cases falls back on the disciplinary knowledge base of the expert. Neither can be eliminated – the appreciation and feel, the praxis, of cases, nor the backbone of formal, abstract generalizations.

Boix-Mansilla [46] writes of interdisciplinary learning as a "series of delicate adjustments" into the previous intellectual commitments on the subject of study. Her stance on the clash of epistemologies is a pluralistic one; more than one knowledge system are utilized and the evidence may not all match up, but the conclusion can be deemed acceptable against the purpose of investigation: does it help solve the problem. Nordmann [47] explores the purpose within nanoscience; he describes the field as an exploration, where (epistemic) success is defined by the ability to act on the nanoscale.

We see the process as weighing disciplinary insights and revising or abandoning previous intellectual commitments in place of more reasonable ones - for the particular problem, on a case basis. In Chari's [36] interviews, a physicist graduate mentalized his disciplinary knowledge in physics as "fundamental

building blocks”, which “worked as a platform to construct new knowledge in his research on.” He learned new disciplinary knowledge by making a connection to his “building blocks” (p. 113).

Boix-Mansilla [46] determines four core cognitive processes of interdisciplinary study: “establishing purpose; weighing disciplinary insights; building leveraging integrations, and maintaining a critical stance.” They are very similar to Repko’s [7] interdisciplinary research process (IRP) model: Drawing on disciplinary insights (define the problem; justify interdisciplinary approach; identify relevant disciplines; conduct literature search; develop adequacy in each relevant discipline; analyze problem and evaluate each insight or theory) and Integrating disciplinary insights (identify conflicts between insights or theories and their sources; create common ground between concepts or theories; construct a more comprehensive understanding; and reflect on, test, and communicate the understanding).

As a parallel to Boix-Mansilla’s outlined conceptual development, Andersen [18] maintains that an interdisciplinary group can develop a (partially) shared conceptual structure. The group members share in the individual substructures that are related to the specific disciplines, each from their own area of expertise.

To apply these ideas in a real-world example, we describe the interdisciplinary process in a research project in nanoscience:

Docent, Dr. Toppari [39] looks back at the determination of conductivity of DNA origami: “During our electrical measurements of DNA origami, we utilized impedance spectroscopy (IS), i.e., multi-frequency analysis, in addition to the earlier direct current (DC) techniques.” The *problem* was determining the electrical resistance of DNA origami. The purpose and *justification for an interdisciplinary approach* came from the inconclusive previous research with monodisciplinary approaches. The chosen, novel method allowed his group to compare and contrast their result with the conductivities of other, previously measured combinations of molecules - other *cases*. From those comparisons they realized that “the main resistance in the DC measurements was due to so-called linker molecules used in attaching the thiol groups.”

With a pre-existing *adequate* understanding of the specific biological and chemical realities of their samples, such as conformation changes of the DNA relative to the adsorbed water layer around it, they noted that the available approaches were in epistemic *conflict*: on one hand one could describe conductivity mechanisms in terms of electric circuits, or on the level of molecular charge transfer and chemical reactions. They *created common ground* between those levels by modeling equivalent electric components for the contributions of ionic diffusion, adsorbed water molecules, etc. [48]. The *more comprehensive understanding* they constructed was an equivalent circuit model of the situation. Falling back on the physical understanding of electric conductivity of combinations of components, they were able to determine the components of resistance for a genuine origami in high humidity and *reflect on and test their understanding* with other ambient conditions.

### ***2.1.3. Slow development from multidisciplinary towards interdisciplinary practise***

It has been argued that the so-called interdisciplinarity of nanoscience turns out to be merely multidisciplinary in closer scrutiny of the actual practices [15], and nanoscience is just an umbrella term for many fields of research with their own approaches and paradigms. For instance, the ideas of atom-by-atom-manipulation and self-assembly are fundamentally so different and rooted in their disciplinary origins that genuine interdisciplinary advancement by utilizing the other method may be difficult to achieve. Nordmann [47], in footnotes, seconds the notion and remarks that while imaginable, there appears to be little pressure or movement toward the development of an integrated thought for nanoscience.

In light of the previous two features of interdisciplinary understanding, we can only acknowledge the difficulty of interdisciplinary research and that of *creating common ground* amidst the viewpoints of different disciplines.

There are examples where epistemological difficulties have not stalled research, but - though perhaps slowly - an interdisciplinary synthesis and a *more comprehensive understanding* has been acquired. One good example is the studies of molecular junctions, mentalized first by some as molecular wires with a statistical distribution of transport properties, and by others as supermolecules, whose structure determines electron transport. The studies have created a middle ground and integrated the conflicting disciplinary mindsets. From such ground a more comprehensive understanding of the problem can be reached - an integrated view of the conductance of molecules [47].

In similar vein, Dr. Toppari describes the mental journey from multidisciplinary origins to integrated understanding of the conductivity of DNA [emphasis added]: “Gone are the illusions of physicists about DNA as a robust molecule which could be utilized in any electrical circuit, as well as the notions of biologists about DNA as purely the carrier of genetic information. *Perspectives have changed within both disciplines*, and more importantly – a common “language” between them has developed to the point of *enabling reliable communication without ambiguities* [39] (p. 113).”

Other examples might include the determination methods of structures of colloidal nanoparticles [49] and function of dye-sensitized solar cells, in particular the discovery that dyes paired with nanostructures were what enables conductance also for the visible spectrum of light [50].

#### ***2.1.4. Journal articles and what they can tell about interdisciplinarity***

Bibliometric studies can be a window into the cognitive identification of people in nanoscience - a tendency to publish research in disciplinary groups and journals [17,51,52]. We start with Schummer’s [15] description of some disciplines as similar to worker bees tending to their queen, without much recognition from the queen. This worker bee role certainly can happen, and for some disciplines it takes place even most of the time - for example toxicology and ethics. While toxicologists analyze the potential impacts of nanoscale particles, the information they produce is seen as additional by the engineers: “[t]oxicology is usually seen as a brakesman and spoilsport. Toxicology focuses on

implications that an engineer does not necessarily see, but which could be of great importance for him [38]”.

In contrast, Rafols & Meyer [53,54] looked at the cognitive level within a research project. They reviewed article citations and references, and argue that there is a high degree of interdisciplinarity as evidenced by the breadth of disciplinary knowledge referenced and the similarity of the references. Huang, Notten and Rasters [55] point out a weakness in interpreting bibliometric studies; the measurement of interdisciplinarity can be undertaken at several levels; cognitive aspects of research, such as the use of references and instrumentalities, or the affiliation and background of the researchers, or the orientation proclaimed by the journal, and still at different levels of detail (a journal - a paper - a citation). This yields contrasting results. For example the contributions of biotechnology are often missed by lexical queries, as they do not explicitly contain the phrase “nano.”

Curiously, one of Chari’s interviewees notes [36], on p. 129, that the graduate students at her lab were not writing with a journal in mind. Despite being the main contributors and constructors of the papers, “they trusted their mentors/supervisors experience in this area and followed their call [on the selection of the journal].” This yet again makes it difficult to make judgements on basis of journal choice alone.

#### ***2.1.5. Mediating role of technology and experimentation***

Nanoscience is closely connected to the technological development: experimentally, nothing can be studied without the technology to excite nanophenomena by controlling sample conditions, or to make the phenomena readily available for investigation. Technology becomes a connecting, interdisciplinary layer for scientists who develop and rely on the same technologies. A technological mindset of “getting it to work” can speed up and encourage the interdisciplinary collaboration when theoretical underpinnings are less critical than showing what’s possible, e.g., electric transport in molecules [47]. The methodologies in experimentation are by nature shareable. Similarly, computational studies in nanoscience can often utilize the same algorithms and computing environments, when the templates on which the computer codes are based [56] are general enough.

How the sharing *actually* takes place is a different question. Fiore [57] found that experimentation and laboratories worked in another manner if researchers from different disciplines were present; they utilized analogies to form shared understanding and a concept base, and the analogies led to modifications in the set-ups. In labs with members from the same background, the conversations took place on the level of standard manipulations as a way to solve problems, rather than a holistic understanding of the methods. Chari [36] calls the questioning of methodology and techniques of instrumentation one of the big interdisciplinary skills. She found that some researchers saw value in “learning [the] instruments” while others associated them as simply “devices” for data collection.

One of the researchers she interviewed did use AFM and scanning electron microscope as part of her research work, but collected the data with the help of a technician and was uninterested in learning those instruments, viewing them as “devices” only [36], pp. 117-119. While the instruments provided an important link between the disciplines, they did not automatically become parts of the shared

conceptual understanding and knowledge world. Working with the instruments and interpreting data was considered as challenging [36], on p. 158, which suggests that the researchers did have to overcome some hardship in negotiating their initial, discipline-centered point of view with a technoscientific, instrument-enabled point of view as they worked to understand what their data could rightly - following the epistemological constraints - be said to represent.

Professor Nissinen from NSC-JYU [39], on p. 51, describes her experience of the collaboration around different discipline-specific research methods and equipment. While the first years were spent with getting to know what equipment was available in the neighboring disciplines, collaborations speeded up the use of instruments. She brings up a specific way of collaborating at the layer of instrumentation; she describes it as “asking for ideas from researchers in other fields as to how they would go about some study.” As a result, her organic chemistry group benefited from the expertise of physical chemists and biologists in spectroscopy. The ideas of other researchers, who had a deep understanding of spectroscopic methods, helped her group members overcome methodological obstacles as they learned to use and interpret fluorescence spectrometers. The collaboration that existed most deeply at the level of instrumentation resulted in joint publications with spectroscopy specialists, and a more comprehensive understanding of, e.g., the fluorescence mechanisms and structural changes in supramolecular assemblies of resorcinarenes [58].

For nanoscience and -technology, we suggest that technology be viewed as one of the domains where the researcher must establish adequate “disciplinary” understanding in; understanding of the different techniques, instruments, and set-ups that goes deeper than a user manual level - knowing what phenomena the instrument is based on, understanding its limitations, and having an idea of how the data is interpreted (either by the user or the device).

## **2.2. Nanoscience as a Socio-Institutional System**

### ***2.2.1. Importance of initial training and socialization in a field***

Becher and Trowler [59] remark, on pp. 47-50, that the institutional affluence is at its largest from undergraduate time to the completion of a PhD, shaping the academic identity of a researcher most intensely. The socialization involves the internalization of the myths and legends that shape one’s worldview into highlighting the role of one’s own discipline, all through interactions with instructors and fellow students, rather than someone “laying down the law.” Gerholm (as quoted in [59]) suggests that being a student in a discipline forms its own set of tacit, disciplinary knowledge, of navigating the subject matter as a learner. In settings where one has only one strong reference group, her facility and ability to develop interdisciplinary interests is much more limited than in an educational setting where one has many.

Socialization in the research community plays an essential role in the education of new scientists, which is a kind of initiation in the culture nurtured in the field. Socialization into the culture of a field means learning about both the methodological and social practices of the field, which can be called as contributory expertise in the field. Contributory expertise enables a scientist to make independent contributions to the field (see [60–62]). In addition to research practices, contributory expertise means

sensitivity for symbols, meanings, and representations. This knowledge forms a “map” the researcher uses to navigate his field, and the basis of his scientific intuition. Such intuition guides both understanding of the subject under study - its methodological and epistemological aspects - and actions of the researcher in the social context. For example, in the book *Epistemic Cultures* [63], Karin Knorr Cetina argues that in the context of high energy physics, experiments have replaced individual persons as the things that produce knowledge in the field. In molecular biology, by contrast, individual persons remain the primary epistemic subjects (knowers). Internalizing the idea of what produces knowledge, the values and purposes within the field, and the ease of operation on basis that others share the same set of tacit, silent knowledge they operate by, the researcher establishes contributory expertise within a field. It is thought to require full-scale physical immersion in a culture [43,60], hence, from this perspective tacit knowledge and experimental skills are part of contributory expertise.

There’s little research on how the picture changes if the culture and the field are interdisciplinary from the start. The interdisciplinary collaboration today is of researchers trained within one field (as described above) extending their contributory expertise to use with colleagues within different fields - as if *trading* on an *interdisciplinary zone* [44]. The features of an interdisciplinary trading zone are that there is a set of shared local rules, allowing scientists or groups with different identities to work together without further commitments.

The interactional expertise of working together can be distributed in different ways in the group [18]. For example, in a study among researchers modeling nanoscience the modellers were concluded to have taken an active role in facilitating the co-operation between the experimental and more theoretical scientists focusing on same phenomena. The task of modelers was seen as to bridge and mediate between theoretical and empirical world, thereby developing both [64].

One’s ability to transfer expertise to other fields is especially important in the scientific fields related to rapidly developing technology, such as computer software and hardware, where new tools and methodologies continue to emerge. On one hand, existing knowledge and methods can quickly become obsolete and on the other, the technological skills and understanding is often highly applicable into new fields. In such rapidly developing fields we thus see successful attempts to bridge different disciplines by experts acting as “brokers” in the transfer of methods and perspectives to other fields or by producing boundary objects transferring know-how [65,66].

When thinking of scientists who studied in interdisciplinary settings and had experiences of interdisciplinary research when acquiring this tacit knowledge, the rules and divisions of expertise may be different from the current picture outlined above. Having disciplinary adequacy in the neighboring fields helps become aware of some of the tensions and their resolutions inherent to interdisciplinary work; as well as acquiring (some) of the tacit knowledge within each field. Socializing into research happening at the trading zone, we expect, leads to an inbuilt expectation of mediating ideas, unsaid rules, and a habit of contrasting and validating them. The contributory expertise would already contain much of the interactional expertise described above.

### ***2.2.2. Forming Interdisciplinary Groups and Institutes***

As so many nanoscience laboratories are relatively new, they still carry a memory of how they were established and what the initial difficulties were. For the researchers that put together a new research group or institute, this feat serves as a grand quest that they undertook together, forging relations between the people from different departments and creating interdependence. Things typically do not go smoothly; one has to settle differences in habits of talking and conventions as simple as which units to express results in, but also more deep differences such as the tacit underpinnings and expectations outlined in sections 2.1.1 and 2.2.1.

At the Nanotechnology Characterization Laboratory (NCL) in Frederick, MD, they recall long, unfruitful discussions over “trivial matters [37].” According to professor Kunttu from the NSC-JYU [39], p. 50, “at first, it seemed as though nothing would come of it. It looked like people were withdrawing to their same, old work.” The people at NSC-JYU mention unifying experiences such as applying for initial and project funding and negotiating and buying equipment for laboratories [39], on p. 36.

The other case is when new people enter the field, without a great unifying experience to draw connections from. Entering a nanoscience research group and learning to be part of the community, a novice researcher adopts the tacit ideas guiding the pursuing and warranting knowledge in the field. When learning by doing, novice researchers are initiated in the ways of action and thinking, they learn to see the situation as those are seen in their own group(s) of reference. Thus, it is largely a question of initiation in an epistemic culture, a kind of understanding tacit rules guiding action in both knowledge building and in relation to others (cf. section 2.2.1.). Prof. Manninen from NSC-JYU [39], p. 61, remarks that the groups that did not migrate under a common roof are more aloof; “There’s an immediate effect when you don’t go to the same coffee room to get your coffee.”

### ***2.2.3. Professional identity***

Eisenberg and Pellmar [67] note that “a virtue of the traditional approach of requiring narrow expertise is that students begin to feel a sense of mastery and develop a professional identity.” There is little information yet on how nanoscience researchers with an interdisciplinary initial training experience the identity struggle - so far they are few and the first are in the post-doc or junior professor phase of their careers. David Botstein, professor of genomics, remarks in [19], “ I don’t believe that my generation or the generation immediately after is ever going to become interdisciplinary in any meaningful sense. It is today’s students who will be the first real interdisciplinary generation.”

Instead, we have quite a good understanding of the process people go through when they migrate from a disciplinary expertise position into an interdisciplinary environment. To change one’s disciplinary expert identity into an interdisciplinary one is difficult, as illustrated by a study into the NCL unit of translational nanomedicine. While realizing the ineffectiveness of their original labels as descriptors of the work they did today, they refused to be categorized as “nanoscientists” [37]. Chari’s [36] nanoscience doctoral students also labeled themselves as disciplinary graduates first, with “skills to research at nanoscale” (p. 163).

Identity formation requires much more than the acquisition of conceptual knowledge. The study into the initial formation of the NCL revealed a strong connection between “knowledge-making, institutional

building, and identity formation [37].” An identity formed during education is very slow to change [67], as it builds so strongly on the contributory expertise gained during one’s socialization into science.

The story of the chief immunologist Dobrovolskaia at NCL [37] provides an example of the identity struggle. As immunologist, her work used to take place at the end of product development, but placed in the lab with chemists and toxicologists she at first “couldn’t find [her] role in the lab.” She viewed her task of detecting amounts of endotoxins in various nanoparticle samples as “textbook knowledge” for every biologist, and was puzzled to discover nanoparticles in fact modulated endotoxin responses in traditional tests. It was by working with chemists and toxicologists that she formulated a methodology to discover whether endotoxins or nanoparticles were responsible for a positive response. Despite contributing substantial content to “nanoimmunology” at NCL, she continued to state her identity as “an immunologist with an experience in nanoparticles”, reasoning that it was the field she trained in - and that “nanoimmunology” as a field, she felt, did not exist at the moment.

The identity of a research group can more easily be perceived as interdisciplinary. The feeling of belonging and community spirit is important in identity formation, and regular, informal meeting opportunities during terms or within summer courses or symposia are viewed as especially important for interdisciplinary students [67,68]. The socialization and membership of such a group can provide a strong feeling of community despite the differing labels on personal identities.

#### ***2.2.4. Establishing academic credibility as a group***

As hinted at previously, interdisciplinary research is at first glance viewed as less challenging and rigorous, for those that “could not succeed in their own discipline”, a way to “lose their professional identity” [67,69]. Such statements reflect the deep socialization to one’s own discipline, and the ease of viewing it as superior to others [6,67,70,71], but also the academic prestige of “pure” research in natural sciences [72]. The more sophisticated critique questions the possibility of valid interdisciplinary research per se; e.g arguments that the epistemic differences are too big to overcome [13,15].

It is important for both a researcher and a team of researchers to feel they are doing credible science and attain a position in the academic world; interdisciplinary research has got to prove its worth and credibility. Some of it may channel into portraying a better picture to onlookers than reality suggests; the NCL personnel remember attending meetings and conferences together to “frame” NCL as unified, integrated entity, “instead of a center hosting individual projects [37].” Nancarrow et al. [73] remark that one reason why a shared mission statement is important is that it portrays an unified picture to onlookers.

But portraying and mimicking can lead to doing the right thing - fake it ‘til you make it - and it certainly is critical to form a collective identity for the team of researchers. A critical mass of resources can be the deciding factor in attracting more resources and funding.

The NCL decided that their credibility must come from “collectivity, not competitiveness.” The collective identity of the lab formed around their special niche: coming together of three special groups and the (forced upon them) task of collaborating with the government, industry, and academia. As for the

aforementioned chief immunologist at NCL, she found that her personal credibility stemmed from her unique skillset, rather than being the “best immunologist”; the immunology at NCL requires interdisciplinary skills, which she believed to be her strength. Ku [37] remarks that discovering this marginal, but essential niche, became the basis of their existence.

The results of this strategy were positive, despite the fact that creating the collective outlook took time. Professor Kunttu recounts in [39], p. 50, “Now I’ve seen and heard of many collaborations springing up. It took a few years, but now it looks really good. Though this is a small department, it is acknowledged highly among Finnish universities.”

The history of nanoscience is ripe with stories of finding a niche, finding a “market” for one’s research interest in the other disciplines. Binnig and Rohrer had a difficult time selling the scanning tunneling microscope (STM) technology to the surface scientists until they hit upon the then unresolved problem of the surface structure of (1,1,1) silicon and imaged the unit cell; it marked the entry of the STM as tool for surface science. Moreover, the building of a STM became an initiation ritual of new postdocs and staff scientists in the field, creating *another* new type of technician/scientist position at the labs. Because the academic groups (unlike corporate labs, such as IBM) were small, they had to find a niche through other means, and started on interdisciplinary collaborations - inviting postdocs or junior professors from other labs to train on probe microscopy, work on their samples, and stack them with an AFM to bring back home [74].

### ***2.2.5. Personal academic credibility; tenure***

On a personal level of establishing credibility, the difficulty of getting tenure as an interdisciplinary researcher in a disciplinary academia is a worrying prospect. When looking at linkages between interdisciplinary graduate research and the advancement of an academic career, interdisciplinary research has at least in the previous years been linked with non-tenure track positions in academia, but the linkage has faded in recent years [75]. We are not aware of a similar study specifically within nanoscience.

Nevertheless, there is some attraction to interdisciplinarity, and some of it can be attributed to finding a personal niche in the academy. The research is seen as emphasizing working with people; the area is relatively new and void of (unidentifiable) role models; it offers a niche for the very specialized skillset; and it may lead to positions of power otherwise unachievable [76]. Rhoten and Pfirman find preliminary evidence to the idea that women are more attracted to interdisciplinary fields; in statistics of time spent on interdisciplinary research, female researchers not only spend more time than males, but draw from more disciplines than males do, confirmed in later studies [77]. Millar as well as Rhoten and Pfirman went on to consider whether the attraction of interdisciplinarity is based on truthful premises, and whether using those “promises” to attract more underrepresented minorities into interdisciplinary science is ethical - considering the slower career advancement opportunities thus far.

Looking at the issue of evaluating a researcher’s performance in an interdisciplinary context, some specific problems arise.

While some papers identify the role of each researcher and their contributions in the paper, others don't. When working in an interdisciplinary context it can be difficult to justify the authorship rank, as the seeming importance of contributions can shift when looking from different disciplines. The time invested in keeping the collaboration going and mediating between actors is also easily overlooked in the authorship rank. Chari's postdoc interviewee notes on p. 125 [36] that "it was not intentional and could have happened due to the lack of awareness of the researchers from other disciplines about the details of that particular task in other disciplines", but reflects on his instructor's comments that going uncredited is commonplace. A similar problem arises with funding and grants - some universities credit the principal investigator only [67] and the merits are not fairly distributed, even when the money is.

Professor Kunttu [39], on p. 50, also reflects on the initial slowness and smaller rate of publications of collaborative research: "Interdisciplinary research is a great thing, but it's tough – really tough. It isn't a problem for those who want to solve big problems, but for those who just want to produce publications, it's a challenge. I try to ensure people that independent, high quality work done here, though it may take more time, is more valuable than riding on someone's coat tails. I think that mentality has started to spread."

The NSC-JYU strategy was also to create a collective vision, where certain common research directions have priority. "If every one of the twenty or so research groups does their own thing, it is difficult to get a credible research proposal or, for example, center of excellence status from the Academy of Finland [39]." (p. 66). The solution was to some degree limit personal desires in favor of a group. It is somewhat debated whether it is difficult or not to get interdisciplinary project funding; in some fields, there are funding sources available specifically targeted for interdisciplinary projects [67], but in general it's not very clear how an interdisciplinary project or a researcher's performance should be evaluated by review committees or the university (e.g., [67,78]).

Securing funding and especially a continuity of funding in context of nanoscience has previously been relatively easy; several countries have or have had a NST funding program (e.g., FinNano programs in Finland between 2005 and 2010, NANOMAT and NANO2021 in Norway between 2001 and 2021, the ongoing NNI in the United States since 2001 - see more cases in *European nanotechnology landscape report* [79]). Many of the funding programs have now finished or are finishing. Without a funding source with a focus on interdisciplinary research, the evaluators of the projects are not necessarily competent to evaluate an interdisciplinary research proposal. As an example, the end of "easy" funding hit during professor Korppi-Tommola's term as the head of NSC-JYU starting 2011 [39], p. 59: "The funding situation was completely different from his first term. The budget was nearly zero and the big projects had just finished up and the funding outlook for nanoscience didn't look as good. The boom was over." The increasing competition over funding can be especially detrimental to long-term, interdisciplinary collaborations that are slow to produce quick, appealing results to the funding agencies.

The suggestions for tackling those problems typically include agreements on the issues within the collaborating schools and the persons themselves, but there are already some toolkits available for

evaluating interdisciplinary research in general. Begg et al. [78] reviews some options and recommends their use already when students train as parts of an interdisciplinary research team.

### **2.2.6. Working alongside people: Trust, openness, teamwork, leadership, and soft skills**

Professor Törmä from NSC-JYU remembers an influential statement from the beginnings of the Nanoscience Center [39]: “I remember him always saying that we should continually praise each other, not ourselves.” The sentiment was to learn to respect other fields’ expertise - if it did not come naturally, it could perhaps be conditioned to take effect. Professor Manninen elaborates on p. 52, “It’s important that different researchers don’t belittle each other. That’s why I set as a guideline that we should competitively praise each other. When we speak positively of our group, we start to believe how good we are ourselves [39].” If the belittling gets the upper hand, the result is the judgement Chari’s [36] interviewees felt in having their research’s value evaluated through the lens of another discipline (see 2.1.1.).

Establishing positive and respectful images of the collaborators and their disciplines can be the starting point. Chari [36] exemplifies on p. 144 this sentiment she encountered in some of her interviews of nanoscientists; “Being there and being accessible was of great importance for Alan. I could detect from Alan’s description that he trusted Siobhan’s knowledge of her discipline and therefore the interactions were valued and cherished by him.” She called this process trust-building, seemingly both in the person as well as the discipline, and viewed it as the basis for being able to use results or methods of another researcher - even when the researchers had no interest in acquiring a deeper understanding of the way the results were produced.

Being able to appreciate different solutions and ways of working is one of the traits - openness - that are linked with doing interdisciplinary research. Stokols [28] lists a few learnable behaviors that facilitate effective collaboration in team settings: respectful communication, maintaining proper etiquette when sending electronic messages, gaining experience of collaborative, transdisciplinary research projects and settings. Begg et al. [78] call for training programs that focus on interactions; the “theory and practice of building and sustaining a high-functioning team, and opportunities to practice interdisciplinary team building, management, and communication skills.”

Social circles of researchers, as Becher & Trowler on p.92 [59] describe, consist of an inner circle - with whom one has ongoing intellectual activity and might send drafts of articles for comments to - and an outer circle, whom one occasionally meets at conferences or whose publications were in the same book. The inner circle, they remark, is quite consistent in size across sciences - about 20 people. For an interdisciplinary researcher, the inner circle has to bloat to include the go-to colleagues from several disciplines - the experts they are able to draw on and bounce their interpretations off of. The managerial skills of keeping up with people become invaluable. The regular, close contact across disciplines [28,67,78] is central in keeping up with current disciplinary knowledge developments and practicing an interdisciplinary synthesis of concepts. Repko [7] notes, on p. 61, that a willingness to collaborate is especially important in technical and scientific research, where teamwork is commonly involved. The

social relations are time-consuming, sometimes downright tiresome - and they require interpersonal or leadership skills, particularly from the one coordinating the work.

Eisenberg and Pellmar [67] emphasize the role of the leader in interdisciplinary work. It demands “credibility as a research scientist, skill in modulating strong personalities, the ability to draw out individual strengths, and skill in the use of group dynamics to blend individual strengths into a team” - leadership skills in general, not discipline specific, other than the “credibility” that establishes an authority. They, as well as Stokols [28], recommend that the leaders have experience in interdisciplinary research, to be able to foresee possible communicative difficulties or to discourage disciplinary judgement where disruptive. Derrick, Falk-Krzesinski, and Roberts [19] also assign the negotiation of departmental issues, such as teaching and finances handling, which can considerably differ from one department to another, to the departmental leaders; otherwise it can easily become a burden on everyone in the community. Relating more directly to research issues, Chari [35] notes that giving nanoscience graduate students a role in initiating and leading research alongside senior researchers had a positive effect on their attitudes toward the collaboration.

### ***2.2.7. Methodological community near and far***

The community that forms around some relevant equipment or theoretical approaches can act as a gateway to NST in general, allowing for example the notation of “nanoscience” in applications or giving a researcher permission to attend certain conferences. There are some mentions of donning the nano label to improve funding opportunities [38] - although the funding opportunities and nano-hype may already be in decline. Mody [74] explains how for example atomic force microscopes are used to forge a connection to a larger NST community with its preferable byproducts:

“By buying an off-the-shelf AFM, training a student to use it, and producing very ordinary nanoscale images, though, these groups are able to connect themselves to a community of people who work on other entities which have a similar nanopresence (which, at Cornell, is quite a large community). The AFM is hardly central to their work – their knowledge of it is fairly circumscribed, only one or two of their students may be adept with it, most of their group’s time is spent preparing samples that will very quickly be put through the AFM as well as other instruments, and they have little intention of ever tinkering with the instrument. It does, however, help them lay claim to the money, attention, facilities, and community that are growing up around nanoscience.”

Sharing a pool of equipment is perhaps more common for a larger research facilities; there the connection to others is also formed around the equipment, whose operation novice researchers come to learn from masters not necessarily within their own group or discipline. Professor Nissinen from NSC-JYU mentions on p. 51 [39] that after initial brainstorming, it is the Masters students who are sent out to “test the waters” with new equipment and methodologies. Chari [36] on p. 121 describes a research setting where the equipment serviced as a meeting place for scientists:

“Ruth worked in a large research cluster and shared many instruments during her PhD research with other researchers. These instruments were part of the central facility provided to the

university. Although, most of the researchers associated with the big research cluster were using these instruments, their research objectives were different, making the central facility or equipment not necessarily central to their research. However, working with these instruments provided postgraduate researchers the opportunity to help each other in the area they were expert in and share their knowledge. It fostered a good atmosphere within which they could carry over the reconstructed knowledge to work with other disciplines.”

She found that teaching others to use the instruments and techniques helped the researchers learn the instrumentation themselves. The researchers formed an appreciation for the “role of senior postgraduate researchers as ‘informal teachers’ in facilitating the project specific knowledge” and continued the informal teaching themselves [36], p. 155. The equipment is a place to set ground for relations to other groups and act as a place to form contacts and establish go-to-person relationships with other groups and disciplines.

### **3. Interdisciplinarity as an educational issue**

As discussed already in the Introduction, interdisciplinarity is an important concept and topical issue not only in scientific research but also in education. Here we elaborate the educational aspects both regarding basic education (primary and secondary levels) and tertiary education.

#### **3.1. General Education**

Bridging and unifying the traditional subjects in school has been one of the most important goals of curricular reforms worldwide for decades. Recent writings on modern scientific and technological literacy have emphasized such interdisciplinarity (see e.g., [80]). An interdisciplinary approach is central in the recent, highly influential trends in science education: Context-Based Learning (CBL), Problem-Based Learning (PBL) and Socio-Scientific Issues (SSI), e.g. [81,82]. In all these approaches, it is generally seen that the use of real-world problems in science education emphasizes the interdisciplinary nature of the sciences and makes them relevant to students [83]. The cross-disciplinary contexts and cross-cutting concepts are introduced into curricula all the way from primary to upper secondary education in order to facilitate students’ understanding of connections and relevance of concepts [22]. This kind of “seeing the big picture” is considered crucial regarding scientific literacy and competences of decision-making in modern societies [80,84]. In the U.S., the National Research Council’s Framework for K-12 Science Education [85] stimulates interdisciplinary science education. They ask for engaging students in science and engineering practices by developing and linking disciplinary core ideas to cross-cutting concepts to explain phenomena and solve problems [23]. Interdisciplinary arrangement, then, includes multiple practices each in the context of multiple core ideas. This develops an integrated understanding of science, which is essential in the future society [86].

Aside from the Next Generation Science Standards (NGSS) in the U.S., there is official endorsement for teachers to integrate school subjects in other countries. For example, the Finnish curriculum [87] and the Swedish curriculum [88] call for cross-cutting concepts and increasing interdisciplinary outlook. The German school development strategy [89] goes even further in recommending that secondary schools develop their own curricula to address certain interdisciplinary topics of importance (e.g., sustainable

development, oceans, or development of landscapes). The German schools are responsible for the development of school-specific programs, approved by the states, granting a lot of pedagogic freedom and responsibility to schools.

Stevens, Wineburg, Herrenkohl, and Bell [90] express their worry that schoolchildren are unlikely to experience the subjects as different and epistemologically distinctive. In fact, most school curricula could be rather characterized as predisciplinary than as interdisciplinary, because they rarely draw on features of disciplines that lead to conceptual and practical advances in knowledge [91]. As a solution, Stevens et al. [90] advocate for a comparative approach to learning: not to displace the subject-specific organization of education, but to systematically create more connections to “help students learn what is unique about a discipline as a way of knowing [epistemology] by learning how that way of knowing compares with others.” Their project combining history and science (PATHS) shows this key interdisciplinary skill to be attainable already in the elementary grades.

The soft skills associated with interdisciplinarity also strongly resonate with the ideas of navigating the society that has intercultural elements and the working life with its ever-increasing combinations of knowledge from varied fields (cf. [7], pp. 39-41).

### **3.2. Tertiary Education**

Newell [25] makes a bold prediction that interdisciplinary undergraduate education will radically increase, on three grounds: the increased diversity and globalization that both demand and teach interdisciplinary and intercultural skills; the greater accountability demanded from the university - he writes that interdisciplinary research is more real-world relevant and applicable - and, lastly, the post-modernistic movement that approves of coexistence of contesting perspectives. It is also known that shaking the departmental single-discipline norms by early interdisciplinary experiences, such as doing student research as part of a research group, predicts future interdisciplinary research paths [28]. Indeed, it follows that as a new generation of interdisciplinary-minded researchers reach positions of power in the academy, they will be more likely to promote interdisciplinary research and education, thus, creating positive feedback [25].

The education of future scientists has been based in the paradigm of the epistemological identity of a researcher. Hey, Joyce, Jennings, Kalil and Grossman [70] describe the socialization of a scientist as adopting the norms and traditions of their superiors, often including the distrust of other disciplines. Co-teaching by experts of diverse disciplines fades out this narrowmindedness. Handling the conflicts due to the differing points of view productively in education provides tools to manage the later work in interdisciplinary teams [78].

In tertiary education, the higher order thinking skills are attainable by students and can be practiced from the beginning. From Repko's [7] model of an interdisciplinary research process, most aspects of the process appear in any tertiary instruction: defining problem, conducting a literature search, reflecting on the understanding. A typical science instruction includes also experimenting and applying. What cannot be practiced in a mono- or multidisciplinary setting is learning the language of discourse over different

disciplines, identifying epistemological differences between them or pinpointing conflicts in their norms or theories. Without them, constructing comprehensive understanding becomes superficial.

Apart from theory building, the special role of technology and instrumentation in science likely requires another category of interdisciplinary skills. In addition to technical performance, these may include identifying sources of uncertainty and fulfilling quality requirements for experimental results or identifying the innate differences between the object investigated and its experimentally based model or image.

Finally, interdisciplinary programs may provide a glimmer of hope in the problem of declining enrolment in the sciences. The competition of the few vacancies in science is hard, which suggests that young students seek a more generally valid education to increase their competitiveness in the labor market. The IGERT (Integrative Graduate Education and Research Training) programs principal investigators communicated to Rhoten and Pfirman [76] that they believed the IGERT programs on bioengineering or environmental systems were what finally increased female enrollment in their departments. They list other programs where the interdisciplinary and problem-oriented approach appears to increase female enrolment, such as in environmental engineering (as opposed to other fields of engineering). In their account, “individuals who feel marginalized within established fields or dislike highly competitive disciplines” are more likely to “seek alternative domains where the size of the research population, the level of peer attention, and the degree of community composition is less developed than in core disciplines.” Their data suggests that interdisciplinarity could serve as a strong entry point into scientific studies for women.

#### **4. Connecting interdisciplinary skills with educational approaches**

On the basis of our understanding of the interdisciplinary features in nanoscience and interdisciplinary science in general, outlined in Section 2, and the knowledge of ways interdisciplinarity can be addressed, benefited from, and supported within education, outlined in Section 3, we see grounds for breaking down the picture into a comprehensive network of skills and means to attain those skills. We present this network in Table 1.

The structure of the table follows the two perspectives we took in the beginning: it is split into sections of cognitive-epistemic and socio-institutional dimensions. Horizontally, we address the possibilities for general as well as tertiary education.

The objectives or skills as well as the suggested ways to address them in education are elaborated in the following Sections 5 and 6 respectively.

<----- TABLE 1 HERE-ISH ----->

#### **5. Objectives for interdisciplinary nanoscience education**

### 5.1. Interdisciplinary “nano-literacy” for all

Due to the great prospects of applications and implications, it seems likely that in the near future citizens have to make more and more decisions on NST issues – both at the personal level, as consumers, and also at the societal and global levels, regarding the future paths of NST. Therefore it has been argued that public understanding of these fields should be enhanced, so that people could better participate in the public debate and make decisions on the related issues [92--94]. Some level of understanding of these fields has been suggested to be relevant concerning up-to-date scientific literacy in modern societies [30,31,93,95,96].

What kind of understanding of NST should an individual have to be considered ‘nano-literate’? Building on the notion of scientific literacy by Bybee [97], Gilbert and Lin [93] specified different levels of such literacy: *nano-illiterate*, *nominally nano-literate*, *functionally nano-literate* and *multi-dimensionally nano-literate*. They argued that *functional nano-literacy* is a reasonable yet also ambitious goal in general education, signifying a person who is able to “use accepted understanding of nano ideas” and “meaningfully discuss a limited range of nano phenomena.”

In science education literature, there is an emerging agreement on the “nano ideas” which are important for general education and scientific literacy. The widely accepted list of “Big Ideas of Nanoscale Science and Engineering” [30] is the consensus result of extensive discussions between experts from a variety of fields. It should be noted that all nine Big Ideas are interdisciplinary by nature: size and scale, structure of matter, forces and interactions, quantum effects, size-dependent properties, self-assembly, tools and instrumentation, models and simulations, and science, technology and society. If being *functionally nano-literate* entails an ability to use and discuss these ideas, it also requires awareness about the variety of research methods and why they are used and that different methods lead to different knowledge (nature of knowledge). The central role of technology in nanoscience was highlighted in the Big Ideas and it also shows up in our suggestion for cognitive-epistemic skills important in general NST education in Table 1.

Apart from this conceptual understanding, as discussed before, being scientifically literate requires interdisciplinary soft skills which are important cultural competences in modern societies [24]. They provide, apart from skills required in any position in the information society, also an ability to realistically visualize oneself in a science or technology profession - whether or not it results in pursuit of such a career. It enables people to better understand what scientists do and how they interact with each other as well as the society.

Such interdisciplinary nano-literacy for all, dealing with the Big Ideas of nanoscience, has been pursued through a number of initiatives to incorporate nanoscience into school curricula [30,31,95,98], but also many measures of scientific outreach and informal education [92,93].

The general awareness and understanding of nanoscience serves not only as an interdisciplinary nano-literacy for all citizens, but also a foundation for higher education aiming at disciplinary adequacy of NST professionals. Such vocational skills, which in part turn out to be extensions of nano-literacy skills, are discussed in the following section.

## 5.2. Interdisciplinary skills needed in NST professions

Referring back to the two-fold picture of interdisciplinarity in nanoscience - the cognitive side and the social side - we see a variety of challenges as well as important opportunities. To combat the challenges and to seize the opportunities, an individual needs different kinds of skills and expertise, as laid out in Table 1. Another level would be added by looking at the function of a group and how it can learn to work together better; here we address skills of an individual, transferred along with him/her as he/she moves from one position to another.

In our review of nanoscientists' experiences of interactions across disciplinary borders, two big challenges were difficulties in understanding the language or approach used, and one's objectives being judged through a disciplinary lens. They both relate to the ideas of disciplinary adequacy, or within the context of working between communities, trading [44]: trade of ideas, methodological abilities, resources, models, explanations and data at a level that is approachable to all parties.

The ability to facilitate the interactions on the trading zone is vital for interdisciplinary projects, as they are reasoned and developed through the comparisons and trades of input from their members. It breaks down to a few more specific skills or objectives; ranging from contributory expertise within one's own discipline (see 2.2.1.) to an adequate methodological and epistemological understanding in other relevant disciplines. A fluent trading means recognizing how others have different methodological backgrounds. It means they work for different practical objectives and thus their objectives in trading are different. Being able to envision objects or tasks through different viewpoints, to a reasonable extent, makes it possible to plan collaboratively and with benefit to all parties. In sum, the basis of trading lies in understanding the viewpoints of one's own community, and can be facilitated by understanding the objectives and basis of viewpoints held by collaboration partners.

In terms of the socio-institutional dimension, finding one's place and contribution at the trading zone equals to establishing a niche based on an evaluation of the strengths of oneself and the needs of others; the niche may lie in bringing in contributory expertise from a disciplinary perspective, or in the expertise in mediating the inputs from different fields and "translating" or modifying the ideas for interdisciplinary contexts. Either skill is supported by the abilities to function as a productive group member or as a group leader, and navigating a social network of people or a more closely collaborating team.

The researchers coming from different fields use different languages. Such languages are at least partly commensurable, because they aim to explain the same phenomenon under study [99]. To be able to build connections between fields, scientists need also develop intercultural modes of communication [100--102]. This means that they have to learn at least some terminology and about the cultures of communication.

Sensitivity for detecting the appropriate register for shared discussion and knowledge of shared or conflicting vocabularies is also an example of the communication skills learnable in nanoscience. Since in NST, groups of different practitioners already tend to have established collaboration, there already is a regular, shared contact language and other means of communication [100]. It includes the shared

metaphors or analogies that researchers have devised to reason their ideas to others without the jargon and discipline-specific vocabulary [57]. Taking part in building the shared language is also a part of building common ground between disciplinary concepts or theories [7] (p. 326).

One of the skills that is critical in interdisciplinary science is identifying these kinds of conflicts and building common ground [7] between the concepts or theories. This requires both knowledge in the disciplines as well as ability to see where the conflict arises from in the epistemological foundations in the fields, and what approaches have potential to fill in the gap. A wide knowledge base of cases (in detail in section 2.1.2.) or a creative skill and intuition of combining ideas or re-defining concepts - including some specific techniques for starting the work (cf. [7], Chapter 11) - are two ways to approach the problem. One way of envisioning the building of common ground is as bringing experiences from one field and indirectly applying them in another - classified as referred expertise [103]. The merging of experiences, ideas, and methodologies can happen also in other ways, such as gradual changes in one discipline or the development of a common language over a research object (outlined in sections 2.1.2 and 2.1.3.). On the social side this is part of being open to value in other sciences and learning to let judgement pass - particularly when the student scientists socialize into one discipline (as opposed to an interdisciplinary context from the beginning). The related skills are about understanding the applicability of different approaches in different contexts and ability to use other kinds of indicators for quality of research than ones that are in use within one's own field.

The demand for different methodologies or approaches and the special nature of technology are the two remaining cognitive-epistemic interdisciplinary features listed in Table 1. The relevant methodological skills relate to utilizing the technoscientific nature of nanoscience and the beneficial collaboration around instrumentation. It's also critical in the sense that without an understanding of the technology producing phenomena or data, the new researcher is in danger of letting artifacts pass as results (e.g., in SPM technologies, see [104], and Chapter 10 [Perspectives on AFM Education by Moore, Pic, Burnham]). Discussing the technology beyond operating rules and using analogies was shown to be beneficial and contingent on the participation of other disciplines. The analogical thinking and trading is enabled by an openness and acceptance of diversity of points of views, leading to diversity of methods and standards applicable [28,46].

Finally we refer to the societal dimension of nanoscience. Sharing in the larger nanoscience community - in distinction from the local community of researchers or the close-knit research team - is a big part of being a research scientist. This is particularly important for students who do not have a nanoscience student community in their local settings; finding a peer group and receiving and offering support, being able to connect with people with shared interests, is essential to navigating the difficulties of interdisciplinary study and research (e.g., [67] p. 61). Alongside with building an (additional) identity in nanoscience, one acquires the role of a nanoscientist in society and skills related to communicating science to various audiences. This we see as a professional skill required in any science position, but perhaps more so in a field that is characterized by large expectations, public interest, and wild scenarios of Grey Goo and the like that raise questions that any nanoscience student can report to having been asked by relatives or new acquaintances.

### **5.2.1. Comparison to existing collections of learning objectives**

The list of objectives has a good alignment with the few other listings of nanoscience and/or interdisciplinary competences, with its limitations: attention to the *interdisciplinary* features of *nanoscience* only. Some differences are illustrated in the following.

Elbadawi [45] conducted a Delphi survey on the competencies that a person working in nanomanufacturing needs. While the target group is slightly different from researchers, it can provide a good comparison. The main competences on pp. 112-113 appear consistently, although not in as much detail (e.g., which microscopies to learn) in our cognitive learning objectives. From the socio-institutional learning objectives he only includes “awareness of of NM teaching and learning, research, commercialization, companies, careers, and business” and “awareness of the national organizations and government agencies involved in Nanomanufacturing”, which in our table appear as nanoscience community and nanoscience in society. The difference in emphasis is due to Elbadawi’s decision to limit the survey to the “nature of the *scientific* knowledge, skills, and practices” involved in nanomanufacturing - nevertheless some of the community membership objectives do appear in his list, showcasing how difficult it is to separate the social from the cognitive in an interdisciplinary effort.

Borrego and Cutler [105] list examples of interdisciplinary learning outcomes that are applicable to engineering curricula, and that could be adapted for nanoscience:

- “Apply [tool or analysis method] to problems in [technical area]
- Describe the perspectives, methods and expertise that [disciplines] bring to [technical area]
- Identify important research problems in [technical area]
- Assemble a team of disciplinary experts to solve a specific problem in [technical area]
- Work with researchers trained in other disciplines to solve problems in [technical area]
- Teach undergraduates and the public about [technical area]
- Write professional reports and papers describing the results of their interdisciplinary research”

While their list is shorter, they appear to have two learning outcomes that are not on our list of objectives or educational actions directly - identifying research problems, and teaching undergraduates and the public. Identifying research problems per se is at the edge of what can be expected from undergraduate students; identifying problems/themes that it is valuable to study with different viewpoints would be a valid learning objective, were the students not already constrained operating within the field of nanoscience, and with freedom to applied perspectives or disciplines on their own. Learning about current research directions does appear - connected with finding a niche and other features of “referring expertise” - but we recognize it’s not quite what Borrego and Cutler envision.

Teaching has been left out also as it’s not expected from undergraduates; however participation in outreach is included in the list of suggested educational actions, as a means of identifying with the nanoscience community and taking on the membership role and responsibility. Teaching would be a natural follow-up when further in one’s studies.

Finally, Repko [106] defines four cognitive abilities developed by interdisciplinary education that interlink nicely with the cognitive-epistemic features in our table:

1. "Ability to take perspective: student is able to use multiple perspectives and methods to solve complicated problems.
2. Ability to develop structural knowledge of an interdisciplinary core idea. A typical outcome of this is a student's interdisciplinary mental model.
3. Ability to integrate ideas of experts in different disciplines. Students are able to create a more comprehensive understanding of a particular problem.
4. Ability to produce interdisciplinary understanding. Students are able to explain a phenomenon or create products "in ways that would have been unlikely through single disciplinary means."

The ability to develop structural knowledge is not on our list; structure and modeling are seen as inherent qualities of all knowledge in natural sciences, therefore parts of any interdisciplinary venture arising from them.

### **5.3. Assessment**

As learning nanoscience must include both factual knowledge - for example, building a network of cases in nanoscience, or learning discipline-specific methodologies and knowledge - and interdisciplinary thinking and working skills, the assessment needs to take into account this nature of the field.

It's imperative to give formative and summative assessment of interdisciplinary skills [107]; the formative assessment provides guidance in interdisciplinary thinking skills, and a summative assessment provides recognition and places value on the learning outcome - which may not be easy for students to recognize on their own. Learning to make connections between existing disciplinary knowledge or learning effective ways to organize teamwork may not appear to pupils as learning - they do not necessarily gain an additional "fact" in the process. Interdisciplinary learning outcomes, such as projects and solutions to real world problems, often go assessed by generic indicators, such as effort or logic of argument, that do not reflect the interdisciplinary features [108].

Spelt et al. [107] write that "interdisciplinary higher education is still being defined not in terms of what students gain in ability but in terms of its own pedagogical characteristics." Borrego and Newswander [109] note that the problem might lie in that science and engineering faculty are used to writing learning outcomes for technical work, but find teamwork or interdisciplinarity to lie beyond their experience - even if they are involved in it themselves. Conceptualizing it as outcomes is difficult. Here in section 5 and the associated Table 1. we have presented one way of framing interdisciplinary learning objectives within nanoscience.

How does one, then, assess the interdisciplinary features of student work? There are at least some examples that can be adapted for assessing nanoscience learning outcomes. First is the targeted assessment rubric for interdisciplinary writing [108]. It provides a qualitative scale ranging from novice

to master levels of interdisciplinary thought over four main categories - purposefulness (as in there is reason to look at the issue from several disciplinary perspectives), disciplinary grounding, integration, and critical awareness - of the learning outcome.

The rubric for writing does not take into account any collaborative skills; their assessment might better rely on metrics that universities or funding agencies use for evaluating researchers. Derrick et al. [19] suggest indicators such as number of collaborators, their fields - in the pupil's world this would translate to knowledge of whom one would work with on different kinds of tasks. Hall et al. [110] uses the concept of collaborative readiness, elicited via the TREC (Transdisciplinary Research on Energetics and Cancer) questionnaire. It is designed to be a measure of how willing people are to collaborate and if they see value in collaboration. Yet another possibility is the resources of the TOOLBOX project [111] that is in practice a formative assessment of the awareness of philosophical or epistemological dimensions of interdisciplinary collaboration. To our knowledge, no evaluation or assessment tool focused on students' interdisciplinary skills within the socio-institutional domain exist.

To assess success and effectiveness of interdisciplinary teaching or training programs as a whole, however, some long-term measurement strategies - alongside with careful, interdisciplinary analysis - are called for. Those strategies include looking at the levels of what comes of the students "whether graduates maintain an interdisciplinary approach in their work, as reflected by the nature of their collaborations, joint appointments in multiple departments, publishing of interdisciplinary papers, or obtaining grants with interdisciplinary themes" but also the institutions: "institutions [might] revise promotion policies, actively encourage collaborations across departments, or promote training programs with interdisciplinary perspectives." Funding agencies in turn may "alter the peer review system, improve profiles for funding of interdisciplinary proposals, or introduce new mechanisms to support interdisciplinary efforts [67]." Such a long-term evaluation of different ways of entering the field and differences between students trained in single discipline or in an interdisciplinary program would be most welcome in nanoscience.

## **6. Recommendations for interdisciplinary nanoscience education**

### **6.1. General approaches and ideas**

An interdisciplinary approach presents challenges to the formal educational system with traditional disciplinary boundaries in both curricula and practices. In general, designing and teaching interdisciplinary courses differs significantly from traditional single subject courses that the teachers and the students are used to [112]. The methods and approaches of interdisciplinary teaching are naturally closely linked to the context - the level of teaching and the prevalent traditions. There are some universal ideas which we suggest to be considered at every level of education.

Scientific activities take place in a certain (disciplinary) framework and paradigm, which define the appropriate means and methods. The interdisciplinary approach demands identifying the rules and assumptions which guide action and thinking – the "latent" in the approach of a discipline [43].

Approaching the disciplines and the philosophical or epistemological questions is not a typical approach in natural sciences, neither in general nor tertiary education. A starting point always is how the knowledge under study has been constructed. This understanding is essential for depicting what the borders being crossed in fact are. From today's point of view, these boundaries are often unreasonable or can be conveniently overlooked, but the disciplinary borders are historical by nature. Thus, it is worth to consider also the situation when the content under study was built.

Integrating teaching not only between natural scientific disciplines, but also with the humanities – as also called per the NBIC convergence [1,33] - can help in reflecting “how science operates.” Understanding disciplinary differences or differences in production of knowledge may also be easier when the differences are clearer, particularly for younger students.

The cognitive and metacognitive state of being an expert<sup>1</sup> is often seen as the goal of education, and practicing in authentic contexts plays a central role in developing it. Interdisciplinary settings are different; they impose limits on the expertise based on a single discipline, and evoke the feelings of being an explorer rather than expert, operating with an incomplete understanding of the field, and enforce a dependence on other scientists - downplaying expertise as *the* goal of education. In interdisciplinary education, we envision a need to develop students' expertises but to avoid making it a central part of being a scientist. An iconic description of interdisciplinary work - “liv[ing] without the comfort of expertise” [118] - argues the case that often expectations of what it is to do science are not met, and are likely based on false premises of science as a fixed set of knowledge and the mastery of that knowledge. Education at all levels should never be about a set of knowledge, but on high levels of understanding, building a working base knowledge to reform and integrate into new ideas. The more connections students develop between the disciplines and scientific practices and methods and the more they understand about the basis of different approaches, the better they will be in solving problems, making decisions, explaining phenomena, and making sense of new information [23].

There are some general approaches that have already been shown to work well in interdisciplinary education, and which are well suited for nanoscience activities, curricula, and university programs. The first is the development of *communication and social skills in the interdisciplinary context* (rather than off-context, separated into “communication” courses) with explicit attention to open-mindedness to different interpretations, civility to opinions, listener skills and other “soft skills” [107]. The other is utilizing *problem-based learning activities*. They justify an interdisciplinary context, whether the participants are from diverse disciplines or just one. For a multidisciplinary group, the object is to develop co-operation to the extent that participants can share objectives. The problem-based activity can be organized around a nanoscientific “boundary object” [44,119], a document, model, or specimen, to which everyone has a different viewpoint, but no shared theoretical basis. The final important

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<sup>1</sup> Expertise studies have concentrated on cognitive excelling. They provide an understanding of expertise as improved cognitive skills, such as improvement of one's problem-solving ability, or as attaining a high-level capacity, requiring in turn a large organized body of domain knowledge and diverse experience (e.g., [113--117]).

approach is *team teaching*, which has been shown to be particularly beneficial, as it offers students an example of the negotiation of disciplinary rules or implicit knowledge [28,78,120].

In the next two sections, we give examples of how the skills needed in interdisciplinary working are naturally developed by interactive methods, in the integrated settings, which encourage reflective thinking. The suggestions are divided into general education, by which is meant the education for every citizen and every profession, and into tertiary education, which refers to the education of future scientists and technologists.

## **6.2. Implementation in general education**

Small children learn mostly in a pre-disciplinary mindset [91]. The questions they are interested in are not limited by disciplinary boundaries. Slowly as they progress through the school system, the latter parts of secondary school begin to offer students pointers to distinguish the natural sciences from each other. Much younger children are able to evaluate types of evidence or statements, as shown by Stevens et al. [90] and Sandoval, Sodian, Koerber, & Wong [121]. The elementary schoolchildren can explore disciplinary features of the evidence in natural sciences through these kinds of interdisciplinary activities.

It is important for children to be able to inquire and not only learn uncontested, consensual, established knowledge - the latter promotes a naive conception of science and a scientific method. In addition, while making investigations and conducting experiments, it is valuable to give pupils the space to voice their questions and ideas and use their findings to make the world better [122]. Nanoscience offers a great context for such interdisciplinary, inquiry-based activities. The problems in nanoscience have several (disciplinary) perspectives and approaches, so they are authentic, complex problems that have justification for being studied from different disciplinary perspectives. There are several products that children are familiar with that involve NST, such as sunscreens or skis, which could be the starting point of an inquiry [123]. Or one may choose some not-quite-nano everyday substances that involve the same kinds of phenomena (e.g., size-dependent properties in different coffee or sugar grain sizes, which are in the micron range at their finest). There are also different toy models, constructible by teachers or pupils, that pupils can operate and learn about NST [124,125]. Using them in class gives the pupils a tangible object to relate to the problems and possibilities of using technology to e.g., image nano-objects.

Problem-based learning is a good starting point for developing the kind of network of cases that Krohn [11] described. The unique nanoscale behavior in each different case can be compared and contrasted against the students' disciplinary knowledge base.

In addition to cognitive skills, the interdisciplinary context of nanoscience should be utilized for learning soft skills. There are many good guides for helping students take part in dialogic collaboration in science classes, e.g., [126,127] or improving their argumentation skills, e.g., [128,129]. Promoting sharing of scientific ideas and teamwork as basis of science significantly helps more students identify as "science persons" as Carlone, Haun-Franck and Webb [130] show in a study of fourth-graders.

Social relevance and making a difference attract people to interdisciplinary science [76]. The surveys and polls on public's perspectives on NST have shown that the general interest is chiefly focused on visions of issues people can relate to, e.g., energy production, pollution or medicine [131,132]. Also, ethical issues related to NST [33] are of public interest. However, it has been argued that using scientific visions in public debate to a considerable extent can result in serious problems of communication between science and society. Balanced and realistic information is needed, and speculative visions should be communicated only deliberately, pointing out also the uncertain and partly unscientific nature of them [29]. Several learning modules of science with an action component - many connected to nanoscience - are provided by the EU-funded Project IRRESISTIBLE [133]. As an example from secondary school, students are given the problem of deciding whether they would allow their school to have perovskite-based windows, and they investigate the benefits and dangers of using perovskite for solar cells. At the end of the project, the students made an informative exhibition of their findings to the school and organized a student vote (Blonder et al., 2015).

Finally, there are certain contents in nanoscience education that are exceptionally well suited for interdisciplinarity on any level of education; such include the size and scale and the size-dependent properties, imaging and models [Burnham chapter reference], nanotechnology applications [Trybula chapter reference], and the socio-scientific issues of those [Blonder chapter reference] - which are in detail discussed within of this book.

Since the shared size and scale of objects forms the basis for interdisciplinary nanoscience research [15,47], and since scale conception plays a significant role in *scientific literacy* [134] and is one of the Big Ideas of nanoscience, it deserves to be discussed briefly here too. Research has shown that people of all ages have substantial difficulties in understanding the structure and properties of matter at submicroscopic scales [92,135] that is now accessed through imagery and description provided by the microscopy and instrumentation in NST. Scientists and educators tend to erroneously assume that lay people are familiar with the basic ideas of the structure of matter and able to comprehend the size and scale of nanoscience objects [92]. An understanding of nanoscience phenomena can only be built on an understanding of atoms as building blocks, including the size of them, and utilizing it as an approximate reference unit of length. Therefore, education should provide learners with possibilities to familiarize themselves with the basics of the dimension and the structure of matter before going into actual topics of nanoscience. However, the scale and the invisibility of nanoscience objects pose several educational challenges [136]. Learners' scale conception may be supported by presenting scales as a continuum with size landmarks, using relative size comparisons instead of absolute sizes, and promoting proportional reasoning [134,135].

## **6.4. Implementation in tertiary education**

### ***6.4.1. Interdisciplinary programs or not?***

A critical question from institutional or education politics point of view is how the education of future interdisciplinary scientists should be organized. Several natural scientists and communities recommend that students acquire a solid understanding of one discipline [19,67,137]. In p. 59 of the report from the

National Academy of Sciences [67], the writers compare pros and cons of the “traditional”, one-discipline approach: “The virtue of the traditional approach of requiring narrow expertise is that students begin to feel a sense of mastery and develop a professional identity. However, neither the expertise nor the professional identity is suited for rapid changes in the life sciences.” The sentiment rings true in NST as well. In a sense, the question is about whether it’s better to make a (difficult) transition in the beginning of studies, or later in life.

Having a major disciplinary affiliation can give students a simple answer - they belong to a certain department and community, which have a large role in building their identity as a scientist, the importance of which was discussed earlier. Particularly in cases where no identifiable community of nanoscience students exist at the university in question, we recognize the students' need to build their identity in the social context of a peer group as higher priority than that of establishing a trophy group called nanoscience students. Within a loosely organized program, “views expressed by interdisciplinary students are frequently ignored because it is not clear who is responsible for doing anything about them. Even worse, no one asks questions, in the first place, that are germane to interdisciplinary students [138]”.

And of course having an affiliation at a specific department does not close doors from learning in an interdisciplinary manner.<sup>2</sup> Learning about the nature of sciences, namely making the disciplinary differences visible, can instill the mindset and pave ground for later interdisciplinary research paths.

More so today, interdisciplinary stances are widely established and can be reasoned. The interdisciplinary program legitimizes the need for interdisciplinary staff effort in teaching, a major challenge for faculties. Calculating institution-specific student involvement or numbers of students is no longer critical when the instructors’ co-operation is necessary to demonstrate collaboration [139]. It also gives the student group a community of their own and the strengthening of this community can be set as a priority - by means of organizing student conferences, opportunities to meet with staff, and involving students in research [28,67,71,120,140]. It provides a peer group for interdisciplinary networking and support for each other as they face similar problems - institutional, social, or cognitive. The international nanoscience community and the student community in particular are also within the students’ reach.<sup>3</sup> In the long run, we begin to see more and more places offer interdisciplinary training,

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<sup>2</sup> Allowing for large minor subject(s), we expect the students to gain a good understanding of the discipline as well - the adequacy that allows students to fully utilize the perspective and the conventions of the discipline. Removing some of the requirements to attend certain courses (especially when there is room for more students) can help interdisciplinary-minded students assemble a relevant study program without signing up for minors in fields. Some requirements are of course relevant, but could be formulated as recommended prerequisites - the students will pass on the informal knowledge of which recommendations are necessary for completing the course, and which can be overcome with some extra effort on the student’s behalf.

<sup>3</sup> The international nanoscience student community gathers every year for the INASCON [141], International Nanoscience Student Conference, already in its 10th year in 2016. Other international

evolving a shared interdisciplinary identity of being nanoscientists, and more career opportunities become available for interdisciplinary-trained researchers (for detailed discussion see [142]).

#### **6.4.2. Developing reflective skills**

A major learning objective is building students disciplinary adequacy; to equip students with explicit knowledge about the backgrounds of their fields of study, its history and philosophy as explained at the highly practical level, and components of expertise they are acquiring in the fields, especially the tacit components [43,143] of the expertise. The challenge of learning the skills needed in research through studying the subjects and working in labs is not that the expert scientists would like to hide something, but that part of the knowledge that new scientists are in the process of gaining is often *unrecognized* (cf. the classification of tacit knowledge in [103]) and not explicitly discussed in education or research labs.

The potential to contribute to the development of expertise on the basis for the explicit analysis of experts' tacit knowledge has been advocated by a number of scholars [144--147]. As a method, we suggest employing a highly contextualized understanding about philosophy of science [64], developed in the third wave of science and technological studies. The scientists build their expertise by reflection. The first step is to understand the need for reflection and knowing how it can be developed. Contextualized philosophy is an effective tool. The reflective ability develops naturally through practicing it, by reflecting on practices they engage in, on the basis and limits of applying the approaches used and developed- and also on the basis and possibilities of the approaches employed by the co-operators, coming from a variety of fields (cf. 2.1). Patterns of reflective questions can be used, for example, in the supervision of student research. Indeed, interdisciplinary contexts - such as student groups or research groups - for discussing and sharing diverse experiences are essential. This is something that students enculturated in single disciplines may never come across in their studies.

Interdisciplinarity do not need to be limited to the different fields of natural science and mathematics only; it is natural to stretch limits to include humanities. In historical times, it was natural that scientists discussed the background of their field in the same documents as they discussed the methods and what we now call the subject of science [148]. The first philosophers of science were often scientists themselves. Nowadays, when scientists have to specialize more and more and such multi-expertise does not appear as frequently, it could be replaced with scientists co-operating more with philosophers and sociologists of science, for example, in order to analyze their field. Such co-operation is likely to be attractive also from the philosophers' point of view, as recently it has become difficult to publish a study in philosophy of science without a reference to an empirical case.

#### **6.4.3. Examples of realized interdisciplinary approaches**

A jointly held seminar with speakers from various disciplines - usually under a shared, larger theme - is perhaps the most common way of introducing interdisciplinarity [67,71,139,140,149]. In part, it is likely because the seminar is separate from and in addition to all other learning requirements. Nevertheless, it can be a good resource for students when it is accessible to them (time and level -wise). Making it

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student experiences are reachable via, e.g., the International Research Experiences for Students (IRES) program sponsored by the NSF, which supports interdisciplinary research proposals as well.

relevant to their education with awarding of credit points or inclusion of assessment can help bring in the students; otherwise, it will compete with activities that appear more compulsory and are direct degree requirements. The aforementioned articles also discuss whether the presence of senior staff is intimidating to students; discussions in small groups rather than only for the whole audience may help alleviate this problem. The discussions groups in connection to the seminar are also grounds for discussing the basis and possibilities of different methods with experts or apprentices coming from other fields, and learning to develop shared modes of communication and cooperation.

Another way to introduce interdisciplinarity without necessarily altering the degree requirements much is adapting laboratory and instrumentation courses. They are often easiest - and possibly the best ones, as they enhance the possibilities for collaboration over instrumentation [36,57] - to adapt. At University of Jyväskylä we have good experiences of doing this with the Atomic Force Microscopy course [125] as well as other, short courses in nanoscience, metrology and NST. The undergraduate Finnish Nanoscience program at NSC-JYU also has compulsory laboratory courses in interdisciplinary groups. The lab environment makes it easy to introduce teamwork, pairing students from different disciplines, and allows for informal discussions around the instruments, working conventions and habits. Adding structured, reflective questions to "traditional" laboratory programs can step the conversations from the operational to the technical or foundational principles level. Knowing that not everybody will be interested in deep understanding of the instruments, it may become more attractive when studied in an interdisciplinary group and context, discussing not only operating principles but also different applications and results using the technology.

One practical way of introducing the communication skills or social skills within context include using structured roles - pre-assigned, or once students become familiar with taking different roles at tasks, allowing self-organization. Mobley et al. [71] provide an example of practicing leadership skills; in a seminar course that involved freely flowing discussions, a need for more structure arose. The course was developed so that it has a coordinator to facilitate the discussions and the role of coordinator was circulated among graduate students. Utilizing role playing tasks can also help with reflection and recognition of disciplinary ideas. Asking students deliberately to look at situations or tasks from the point of view of a single discipline - as chemists, biologists, physicists, engineers - gives them access to exercising recognition of the tacit, implicit, and latent in a disciplinary mindset [43] as well as processing some preconceptions or judgements they might have of the neighboring disciplines.

Ensuring that students do research in interdisciplinary research groups during their studies - graduate but also undergraduate - has a high payoff. The possibilities for reflection (see 2.4.2.), finding role models and building one's identity as a research scientist, and learning conventions of negotiating disciplinary conflicts or using analogies in discussions, are not available elsewhere with such intensity. Experiences of organizing interdisciplinary student research are well documented (for examples, see [120,137,140,150]) and positive, often yielding research papers as well as motivational benefits.

Using student research as a means in students' identity building and association with the research community is widely employed in single disciplinary settings; it serves the same purpose also in

interdisciplinary nanoscience. Equally helpful are other means of associating oneself with the nanoscience community, such as participating in outreach or student community activities. We also acknowledge the motivational side of using science as a means to act in the society; organizing projects or collaborating with companies (also a means of networking and establishing one's name for the future), and discussing societal problems and taking action on them (see e.g., [122]). An initial societal point of view can be helpful also in directing thought towards why certain things are pursued in NST (is there a benefit for society?) and further reflecting on what is characteristic to research in nanoscience.

During such courses it is natural to employ methods developing skills needed in communication and co-operation, such as teamwork and team teaching. Student-centered and constructive methods supporting creative usage of ones abilities and co-operative problem solving are natural. For example, a problem-based learning group work starts naturally by identifying disciplinary-specific features in knowledge provided (e.g., role play, vocabulary exercises if needed), goes then on to the identifying of conflicts between disciplinary perspectives and to building common ground across conflicting views.

In conclusion, an education that aims to support the cognitive and social development of young scientists, and offer contacts with other disciplines and researchers, is natural to organize in interdisciplinary co-operation. The co-operators available include (but are not limited to)

- the practicing scientists, employing different methods in their research practices and willing to reflect on their knowledge-building, via team teaching courses or supervising student research;
- researchers analyzing the nature of scientific knowledge (e.g., philosophers);
- societal actors and industries providing a background for all scientific activities, and
- the peer group of interdisciplinary students.

Without a long history of interdisciplinary research work to model processes after, the teaching of interdisciplinary nanoscience is very much connected with learning interdisciplinary nanoscience and crossing the disciplinary borders alongside the students [151]. It can be a learning experience for the instructors, and without the burden of how things have been done in the past, a venue for trying new ways of organizing university teaching and studies - such as introducing team teaching, role playing tasks, or collaborative or brainstorming techniques.

## **7. Summary and Conclusion**

Our detailed review of NST research practices and their comparison with findings from other interdisciplinary studies show that nanoscience is inherently interdisciplinary. While the environment and practices may not all reflect interdisciplinary thinking or collaboration, the reason is not that the field or the objects of study are not suited for interdisciplinary investigation. It's rather that doing interdisciplinary work is difficult, and that people are capable or willing to realize it to varying extents. The combination of disciplines in the field as a whole is quite established, but participation from all disciplines is not realized in all activities within the field, nor are the publishing or financing channels set in stone. It is the field that currently educated nanoscientists - whether coming from disciplinary or interdisciplinary programs - are still finding themselves in.

This means there is a need to address the problems withholding people from realizing interdisciplinarity to a greater extent - to enable nanoscience researchers to make decisions based on their own interests or the needs of the field, rather than on preconceptions or institutional barriers. By supporting today's students and researchers in this, we expect to see the positive feedback loop described by Newell [25]. One indirect result might be the fostering of NBIC convergence - the greater convergence of sciences, envisioned as the next big step in science [1].

Taking a step back from the research world, we envision benefits for all citizens from learning sciences with an interdisciplinary mindset. Both the cognitive and social skills supported by interdisciplinary activities will be beneficial in today's world. Helping children put presumptions and biases aside and develop an open outlook, looking for the value and rigor in all sciences, and looking for the value in all people, are big goals. We have shown in the sections above that we can and should use interdisciplinarity to strive towards this better world.

In addressing general education, one cannot forgo the role of teachers in any reform. Since the background of teacher education is in academic system dividing sciences into disciplines and school subjects, it produces teachers socialized in the disciplines themselves - or in the mindset of knowledge grouped in disciplines. The educational reforms of Germany, Finland and the United States are already inviting teachers to cross those disciplinary borders and explore the ideas of disciplines or different ways of knowing at schools.

Our ideas of reaching across the disciplines with nanoscience should be pursued by engaging and supporting science teachers through professional development programs, networking possibilities, and material resources. Teachers' views and needs have been analyzed and recommendations for addressing them presented elsewhere [98,152,153]. Teacher professional development as well as the development of teaching and learning materials should concentrate on interdisciplinary unification of the existing school science, rather than on including additional nanoscience modules in the curriculum [98]. Professional development for university researchers, lecturers, mentors, and supervisors on interdisciplinarity and its implications for their students, if not themselves, is similarly necessary ([107]; examples and possibilities outlined in [71,111,149]).

The development of the features of interdisciplinarity into the skills required and approaches in education is the first step in enhancing interdisciplinary education. The application of these approaches has already begun by those to whose work we refer; the use of an interdisciplinary approach in a large scale, the evaluation of best practices, and investigation of the results of such reforms - particularly long-term - are the following steps. In this path, the students learning interdisciplinary nanoscience today continue to have a contribution to both the science and science education of tomorrow.

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Table 1. The interdisciplinary features of nanoscience and engineering and their implications for education. The features and skills are divided into the cognitive-epistemic and socio-institutional dimensions according to their foundations in Section 2. The skills related to the features and examples of educational approaches are addressed in both general and tertiary education.

	Interdisciplinary feature of nanoscience	Objectives or skills		Examples of educational approaches to target objectives	
		General education	Tertiary education	General education	Tertiary education
Cognitive-Epistemic dimension	<b>Drawing from relevant disciplines</b>	<ul style="list-style-type: none"> <li>Knowing what different fields are about</li> <li>Basic knowledge and literacy</li> </ul>	<ul style="list-style-type: none"> <li>Contributory expertise in a discipline</li> <li>Disciplinary adequacy in relevant disciplines</li> <li>Ability to look at problem from the viewpoint of another discipline</li> </ul>	<ul style="list-style-type: none"> <li>Analyzing how different fields contribute to the issue under study</li> <li>Using interdisciplinary contexts</li> </ul>	<ul style="list-style-type: none"> <li>Wide basic studies in relevant disciplines encouraged</li> <li>Same problem/concept approached in many disciplines (e.g. energy transformations)</li> <li>Study of articles from different disciplines, recognizing disciplinary representations and writing styles</li> </ul>
	<b>Demand to apply a wide range of methodologies</b>	<ul style="list-style-type: none"> <li>Learning that and why different disciplines employ different methods, e.g., experiments vs. computer modeling</li> <li>Realizing special methods are needed to observe nanoscale phenomena</li> </ul>	<ul style="list-style-type: none"> <li>Understanding how the situation is seen by researchers with different methodological approaches</li> <li>Familiarity with different methodologies</li> <li>Striving for triangulation</li> </ul>	<ul style="list-style-type: none"> <li>Using variety of methods when studying a phenomenon</li> <li>Evaluating methods when studying a phenomenon</li> </ul>	<ul style="list-style-type: none"> <li>Working in a research group</li> <li>Shared laboratory work courses between departments</li> <li>Assessment of use of triangulation in lab work</li> </ul>
	<b>Recognition of epistemological rules</b>	<ul style="list-style-type: none"> <li>Understanding that different methods lead to different kinds of knowledge</li> </ul>	<ul style="list-style-type: none"> <li>Reflection of contributory expertise</li> <li>Awareness of disciplinary boundaries and styles</li> <li>Connecting reasons for different styles with epistemology</li> </ul>	<ul style="list-style-type: none"> <li>Choosing approaches for school investigations that reflect the nature of science</li> <li>Explicitly highlighting nature of science</li> </ul>	<ul style="list-style-type: none"> <li>Supported reflection with rubric or guidelines</li> <li>Explicit discussion about the basis of decision making in research group</li> <li>Tasks with pre-assigned disciplinary roles</li> <li>Interdisciplinary discussion groups</li> </ul>

					and seminars
	<b>Technology as enabler of NST</b>	<ul style="list-style-type: none"> <li>Recognizing special technology is needed to observe nanoscale phenomena</li> <li>Understanding that technology can interfere with phenomena</li> </ul>	<ul style="list-style-type: none"> <li>Awareness of how observing phenomena is interconnected with technology used to measure or produce the phenomena</li> <li>Alertness for artifacts/errors</li> <li>Striving for triangulation</li> </ul>	<ul style="list-style-type: none"> <li>Studying the working principles of novel technology that has a connection to nanoscience (e.g., atomic force microscopy, electrophoresis, mass detection with cantilever)</li> <li>Using toy models of nanotechnology objects at macroscale</li> </ul>	<ul style="list-style-type: none"> <li>Shared laboratory work and experimentation courses</li> <li>Analyzing the technology to get and interpret data</li> <li>Tasks to recognize artifacts or errors</li> <li>Interdisciplinary discussion groups or seminars on methodology behind the technology</li> </ul>
	<b>Conflicts between theories and epistemologies</b>	<ul style="list-style-type: none"> <li>Identifying different types of knowledge</li> <li>Recognizing concepts or theories can conflict because of different initial assumptions or perspectives, but still remain valid</li> </ul>	<ul style="list-style-type: none"> <li>Separating conflicting theories or concepts from incompatible results</li> <li>Identifying conflicts between theories or concepts arising from different perspectives or initial assumptions</li> <li>Creating common ground between concepts</li> </ul>	<ul style="list-style-type: none"> <li>Age-appropriate study of theory of knowledge or philosophy</li> <li>Science argumentation</li> <li>Debates</li> </ul>	<ul style="list-style-type: none"> <li>Explicit discussion about the basics of decision making in research group</li> <li>Reviewing examples of common ground building in journal articles</li> <li>Writing articles and reports</li> <li>Team taught interdisciplinary courses</li> </ul>
Socio-Institutional dimension	<b>Network and membership skills</b>	<ul style="list-style-type: none"> <li>Self-evaluating one's strengths</li> <li>Knowing where to look for information from a particular perspective</li> <li>Being able to co-operate in group tasks fairly</li> </ul>	<ul style="list-style-type: none"> <li>Ability to reason own field and its methods for outsiders</li> <li>Establishing relations to others</li> <li>Knowing whom to go to for ideas or feedback</li> <li>Keeping up relations, offering reciprocity, acknowledging help (e.g. in publications)</li> </ul>	<ul style="list-style-type: none"> <li>Practice of self-evaluation</li> <li>Tasks to seek information from persons rather than Wikipedia</li> <li>Collaborative learning methods (e.g., jigsaw technique) to learn sharing first and later sharing the work in a way the group sees best</li> </ul>	<ul style="list-style-type: none"> <li>Working in a research group</li> <li>Shared laboratory work courses between departments</li> <li>Interdisciplinary discussion groups and seminars</li> <li>Collaborative learning methods</li> <li>Tasks with pre-assigned roles</li> </ul>
	<b>Finding a niche and establishing identity</b>	<ul style="list-style-type: none"> <li>Self-evaluating one's strengths</li> <li>Recognizing different demands and benefits of different career paths</li> </ul>	<ul style="list-style-type: none"> <li>Developing a sense of belonging within a discipline and/or in the nanoscience community</li> <li>Acknowledging difficulties and benefits of doing interdisciplinary work</li> <li>Consciousness about identity development and its impact</li> </ul>	<ul style="list-style-type: none"> <li>Practice of self-evaluation</li> <li>Career advise or counselor meetings</li> <li>Finding relatable role models in science or other professions</li> </ul>	<ul style="list-style-type: none"> <li>Working in a research group during studies</li> <li>Hearing from faculty, alumni, or senior students about different career paths</li> <li>Learning about current research directions</li> </ul>

					<ul style="list-style-type: none"> <li>• Reflection of identity</li> </ul>
<b>Acknowledging value in other disciplines</b>	<ul style="list-style-type: none"> <li>• Assessing new people, information, or directions without prejudice</li> </ul>	<ul style="list-style-type: none"> <li>• Recognizing validity of research done in methodologies of other disciplines</li> <li>• Judging whether a discipline's validity protocols apply in particular situation</li> </ul>	<ul style="list-style-type: none"> <li>• Learning to recognize bias and reasons for bias</li> <li>• Hearing about interdisciplinary science and its results</li> </ul>	<ul style="list-style-type: none"> <li>• Working in a research group</li> <li>• Shared laboratory work courses between departments</li> <li>• Wide basic studies in relevant disciplines encouraged</li> <li>• Conscious effort to stay open to different methodologies and results</li> <li>• Team taught interdisciplinary courses</li> </ul>	
<b>Collaborating closely</b>	<ul style="list-style-type: none"> <li>• Giving and receiving feedback and criticism</li> <li>• Collaboration, decision making, task-completion, trust-building, conflict-management and communication skills</li> </ul>	<ul style="list-style-type: none"> <li>• Giving and receiving feedback and criticism</li> <li>• Adapting talk for discussion at shared level</li> <li>• Collaboration, decision making, task-completion, trust-building, conflict-management and communication skills</li> </ul>	<ul style="list-style-type: none"> <li>• Collaborative learning environments,</li> <li>• Shared tasks to practice division of or mutual labor</li> <li>• Open prompts from individual to group ideas</li> </ul>	<ul style="list-style-type: none"> <li>• Collaboration technology and tools</li> <li>• Progress reports</li> <li>• Pre-assigned roles in tasks</li> <li>• Responsibilities shared within student group with gradually lessening faculty input</li> </ul>	
<b>Mediating disciplinary perspectives and people</b>	<ul style="list-style-type: none"> <li>• Experiences of organization and leadership roles</li> <li>• Negotiating differences in habits</li> </ul>	<ul style="list-style-type: none"> <li>• Organization and leadership skills</li> <li>• Recognizing differing ideas of importance or validity of research</li> <li>• Negotiating differences in habits</li> </ul>	<ul style="list-style-type: none"> <li>• Open inquiry tasks</li> <li>• Structured roles for group tasks</li> </ul>	<ul style="list-style-type: none"> <li>• Project-based tasks</li> <li>• Tasks to use knowledge of epistemology to foresee conflicts</li> <li>• Working in varied groups, initially under pre-assigned roles</li> <li>• Leadership studies</li> <li>• Team taught interdisciplinary courses</li> </ul>	
<b>Creativity</b>	<ul style="list-style-type: none"> <li>• Discussing and developing one's own ideas and methods</li> </ul>	<ul style="list-style-type: none"> <li>• Utilizing input from others to create new ideas</li> <li>• Coming up with hypotheses to test</li> <li>• Suggesting methodologies for others' research</li> <li>• Recognizing and applying non-visual</li> </ul>	<ul style="list-style-type: none"> <li>• Ill-structured problems</li> <li>• Brainstorming techniques such as round-robin, mind-mapping</li> </ul>	<ul style="list-style-type: none"> <li>• Working in a research group</li> <li>• Tasks to apply familiar methods/theories to new objects/settings</li> <li>• Brainstorming techniques such as</li> </ul>	

			analogies		round-robin, concept mapping
	<b>Nanoscience community and nanoscience in society</b>	<ul style="list-style-type: none"> <li>• Understanding ethics and politics' effect on science</li> <li>• Understanding how development of NST is dependent of a net of actors in society</li> <li>• Responsible Research and Innovation</li> </ul>	<ul style="list-style-type: none"> <li>• Finding meaningful ways to connect with larger nanoscience community</li> <li>• Taking responsibilities in society as nanoscience expert</li> <li>• Representing nanoscience</li> <li>• Responsible Research and Innovation</li> </ul>	<ul style="list-style-type: none"> <li>• Socio-scientific issues in the context of nanoscience</li> <li>• Inquiries on commercial products</li> <li>• Connecting with local institutes and businesses</li> </ul>	<ul style="list-style-type: none"> <li>• Interdisciplinary student groups within department</li> <li>• Student conferences (INASCON) or (research-inclusive) exchange abroad</li> <li>• Socio-scientific issues in context of nanoscience</li> <li>• Participation in outreach projects</li> </ul>