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CHEMICAL REACTIONS AS *PETITE RENDEZVOUS*: THE USE OF METAPHOR IN MATERIALS SCIENCE EDUCATION

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Abstract

Every time we communicate our science, we are involuntarily involved in an educational activity, affecting the listeners' methodology and motivation. In a beautiful metaphor, late Nobel Laureate, Richard E. Smalley compared interacting atoms and molecules to boys and girls falling in love. Elaborated and exemplified with a couple of entertaining analogies in this discourse is the effectiveness of the use of metaphors in illustrating scientific concepts to both scientific novices and peers. Human brain has been considered to be a complex neural circuitry for the computation of metaphors, which explains the naturalness of their usage, especially when solid arguments could be given in support of the thesis that scientific imagery in general presents a collection of mathematically operable metaphors. On top of this, knowledge could be enriched through logic alone, but new concepts could be learned only through analogies. The greater pervasion of metaphors in scientific presentations could boost their inspirational potential, make the audience more attentive and receptive to their contents, and, finally, expand their educational prospect and enable their outreach to a far broader audience than it has been generally accomplished.

Keywords

Analogy; Classroom; Education; Materials Science; Metaphor

1. INTRODUCTION: OUTLINES OF THE PROBLEM

As many times before, I begin a discourse with a blank line. Indented, with nothing in it. A signature one in my communication style, some might notice, even though every time it is a different point that I am trying to make by its means. And isn't it fun when nothing is used to illustrate something? Were we to succeed, how much more could we depict using something? The beauty of this act lies in the fact that when we find richness in nullity, all things existing might suddenly receive a chiaroscuro of pure magic around them.

Here the meaning of this line of nil is to depict the deadness that the current spirit of the materials science community embodies. This is *the* problem that this discourse will tackle. For, if you struck up a conversation with a stereotypical materials scientist of the day about art, creativity, philosophy or the meaning of life, chance is that staring at one such blank line would bring you more imaginative insights than that talk.

Another line that comes to mind at this point is that uttered by a boy onboard the diamond-laden ship in Joseph Conrad's Heart of Darkness: "Mistah Kurtz, he dead". This refers to the novel's antiheroic protagonist, an epitomic explorer who had ventured deep into the heart of a river in search of diamonds and, after he had found them, decided never to return. He is, of course, symbolic of all the Faustian seekers of knowledge who, having found it, decide to make it an end in itself rather than a means to an end, a route to beautiful living.

Nietzsche once said that if you look for too long into an abyss, the abyss will start looking back at you[1], presumably wishing to tell us that we essentially become what preoccupies our attention and what we wish to create in the world around us - a karmic law in its essence. And when the inanimate world of crystals is the one one's research attention is confined to on day-to-day basis, one starts to naturally reflect this inanimateness in each and every aspect of one's personality. Conversely, spontaneous reanimation of the spirit tends to befall those who roam through the realm of living cells and other biomolecular systems. Now, if you paid a visit to, let's say, the offices of Nature magazine in New York, you would realize that its designers carefully thought about this difference, at least implicitly, and acknowledged it by having literally lifted a wall between materials scientists and life scientists. This wall seems quite unnatural to those of us who have become fluent in both of these basic languages of natural sciences, but that is a story that I will skip for now.

What we are here to discuss is another dichotomy, the one deeply rooted in our cognitive apparatuses, the machinery of our thinking. Namely, our thinking operations could be broken down to two basic elements: logical and analogical. Erasure of either one of them would cause our reasoning schemes to go haywire. Deprived of logic, we would become a lunatic incapable of inferring even the most obvious syllogistic arguments from coincidental thoughts. Deprived of the ability to draw analogical links between pairs or multitudes of ideas, everything we hear would be understood literally and our communicational abilities would equally dwindle.

Consider the following statement for example: "Tall trees need to evaporate water off their leaves to sustain the pressure gradient and the suction force that draws the water from the roots upwardly". One logical inference at this place would be that cohesion of water molecules along the water column in xylem ought not to be disrupted if the tree is to sustain the distribution of water throughout its stem, branches and leaves. One out of an infinite number of analogical inferences would be that a difference in electric potentials is crucial in driving current from one side of the circuit to another. Another, far more poetic inference would be that we need to give the most precious substance that we hold within in order to be watered well – a seemingly paradoxical statement, like all the truest ones in the cyclical reality of ours wherein causes and effects always blend into one. It is this other type of analogical inferences, holding tremendous ethical and aesthetical potentials, that I will try to demonstrate here as vital for saving the materials science from its steady fall from grace in which it is engaged now. But first some examples.

2. CHEMISTRY THROUGH THE KALEIDOSCOPE OF A MUSTARD SEED, THE UGLY DUCKLING, AND FALLING IN LOVE

In an attempt to highlight the impossibility of controlling a chemical reaction by paying attention to its reactants only and denying the physical contexts in which they react, a late Nobel Laureate in chemistry, Richard E.

Smalley used the following analogy: “Much like you can't make a boy and a girl fall in love with each other simply by pushing them together, you cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler-fixed frame of reference. Chemistry, like love, is more subtle than that. You need to guide the reactants down a particular reaction coordinate, and this coordinate treads through a many-dimensional hyperspace” [2]. Now, that representing atoms and molecules as boys, buses or butterflies all makes sense can be justified by the fact that their actual concepts are not true images of the basic ingredients of our physical reality. Rather, they are humanly derived concepts and are metaphoric, not realistic by any means, as such[3]. The fact that these models have been proven over time as useful in predicting the evolution of microscopic physical systems cannot be a proof of their truthfulness, lest we commit the elemental philosophical fallacy of concluding about the veracity of a postulate from the fact that inferences derived from it match the reality. Instead, this fact can only be a sign of their pragmatic value. One such perspective clearly justifies the use of metaphors in describing specific scientific concepts, such as the following:

2.1. Acids and bases as romantic couples

Asked to describe the concept of strength of acids and bases to a combo of middle school students, I asked in turn a boy and a girl from their group to stand up and hold their hands. First I told them to imagine that they are a macho man and a femme fatale looking at each other while constantly flirting with their surrounding and eagerly waiting on the chance to escape from each other’s arms. Then I asked them to imagine that they are a clingy, needy couple where the two partners rigidly stare at each other and neglect the many wonders of the world around them. Whereas the former would be a depiction of an aggressive, strong acid or base, extremely prone to dissociation into reactive units, the latter would reflect a very weak and nonreactive one. And yet, we could hypothesize that the right way is the middle way between these two extremes, whereon we embrace each other with trust and care, but without ignoring the wondrous impressions of the world around us. Truly, if we looked at the acids and bases utilized by biological systems as well as the drugs that humans consume, we would quickly realize that they are practically always weak acids or bases. Proteins are, for example, made of chemically and physically intertwined amino and carboxyl groups, which act as weak bases and acids, respectively. Nucleic acids that store and regulate the genetic information within the cell are also composed of sequences of weak, so-called nucleo-bases and phosphate groups, the latter of which are used in biology as reliable energy-storage atomic groups in ATP and as buffers in the blood exactly owing to their comparative weakness. The ethico-aesthetical point I wished to make with this allegorical explanation was that neither constantly holding hands with creatures we are fond of nor keeping them at bay and depriving us of their precious touch represents the best choice. Rather, switching between the moments of selfless and intimate oneness and of bouncing away so as to explore the world in pure aloneness hides the secret of truly fulfilled living, of rendering us capable of displaying wavy weaknesses that are the actual sources of strength, resilience and creativity in life. A nice counterexample callable upon at this point could be that of gold, the most inert and the noblest of all the noble metals. Paradoxically, its nobleness and the immense monetary value ascribed to it are due to its being the least reactive metallic element, prone to react with no other element but itself, epitomizing extraordinary selfishness in the realm of materials chemistry. The self-centered forces packed into it can be recognized as the total opposites from the virtues in life worth endless praise, which are, as a rule, all about reaching out and giving selflessly. An invaluable ethical and ontological discourse could now start to develop around our wonder over whether there may be a correlation between the microcosmic and the macrocosmic standing behind the fact that this particular metal caused more misery to humankind than any other chemical element of the periodic table, as if its intrinsic selfishness has been reflected in the curse of soul-corroding greed that has centered around it for millennia.

2.2 Is it hydroxyapatite or a hobbit?

My favorite description of calcium phosphate, the chemical compound of which the mineral component of bone is made, is “Nature’s perfect imperfect material”, the epitome of the lifesaving smallness of Winnie-the-Pooh’s friend Piglet in the forest of inorganic chemistry, a little, ugly-duckling-like animal that becomes useful in their adventures because of being small enough to climb out through a small hole in the roof of a house in which he and his friends were locked, call for help and have them all saved by the end of the day[4]. Truly magical it is to realize that the superior strength of bone is owed to the low tensile strength, poor fracture toughness and other considerable mechanical deficiencies of its ceramic component, far more breakable *per se* than Chinese pottery, being akin to hobbits on the run to vanquish the evil forces of the world and make goodness prevail once more[5]. They were rejected at first by their comrades as weak, slow, incompetent and cowardly, and only later, in the course of their quest, while freely expressing their doubts and weaknesses and ceaselessly wondering if they have found themselves on the right track, quite unlike their wicked adversaries who were certain about their path at all times, they proved their role in this lifesaving mission to be irreplaceably essential. For, calcium phosphate is neither strong like diamond nor flexible like guar gum; nor lustrous like sapphire nor transparent like jade; nor colorful like opal nor chatoyant like moonstone; nor smooth like glass nor silky like butterfly wings; nor precious nor difficult to make; nor conductive, acoustic and elastic like metals nor able to create a magnetic aura around itself. Rather, it is pale, fragile, rough, cheap and crumbly, but in spite of all of that, Nature, as if wishing to teach us something of tremendous importance therewith, chose it as the main ingredient of the bases of our bodies.

Could she have given us a sign thereby that to openly express our frailties rather than hide behind the veil of phony spotlessness is the road we ought to take? Was that her message for the humble and the sensible that for as long as we defend our stances and believe in the perfection of our worldviews, opinions and acts, we would be far from the perfect way of being? Did she mean that the moment we discard the thoughts of our own immaculate-ness and adopt a humble preparedness to accept the inevitable fallaciousness of our own thinking and behaving, the doors through which a gentle flow of creativity and inspiration could enter our being would open in all their charm?

2.3. What the tooth enamel, the most famous corn of wheat, a bridge burned down and Juliet Capulet standing on a starlit Veronese balcony have in common

My research conducted in the lab with a view of the Golden Gate Bridge aimed to demonstrate the fallacy of the then standard description of the mechanism of amelogenesis, that is, tooth enamel formation in vivo, and derive a more advanced model thereof[6]. According to this old school view, the growth of extremely elongated hexagonal crystals of apatite that comprise enamel is explained by the specific adsorption of nanoscopic amelogenin spheres onto all but (001) faces of the given crystals[7]. They are presumed to effectively block the diffusion of ionic growth units from the surrounding gel onto the crystal surface, hindering its growth, which then proceeds strictly along the direction of [001] crystallographic axis. The results I obtained in the lab, however, challenged this view by showing that the way enamel grows was not by amelogenin nanospheres' adsorbing onto specific crystal planes and inhibiting their growth, but quite opposite, that is, by their adsorbing onto the growing crystalline faces and then channeling the influx of ions to the underlying crystals[8] (Fig. 1). What was implicit in this finding did not only shift the current paradigm in the field of enamel growth, but it also carried valuable insights for the much broader field of biological mineralization as well as for understanding the protein-mineral interactions in general, and all that while offering a sweet new metaphor. Namely, it showed that Nature does not use its "peptide powers" as ignorant gates that reject the incoming ions and inhibit the growth of things that adhere to them, but has evolved them in such a manner so that they can build things up by transmitting, yielding, and creatively placing the building blocks that knock on their doors onto the right places. "Not walls, but bridges they are", I could have been heard saying to my peers in the days of this discovery, while carrying the vision of the epigram Banksy stenciled on the infamous 700-kilometer-long apartheid Wall that separates Israelis from the Palestinians, the modern epitome of architectural vulgarity. Drawn on it is the shadow of a girl with braided hair being lifted up high in the air while holding a handful of balloons, wittily demonstrating the ethical and aesthetical necessity of flying over the artificially imposed walls, if not ruining them altogether. An excellent teaching experience is exactly such – it is all about fostering the flights of spirit of the little ones instead of guarding the gate and letting them down. It is about giving everything and thereby silently, implicitly inspiring great intellectual thirsts in them as well as the enlightening cravings to give, give and give, with no end in sight.

Another aspect of this biological process offers room for an even more inspiring, though closely related, metaphor. Namely, the hardest tissue in the vertebrate body that enamel is forms by filling up the space initially occupied by a protein gel, which, as the enamel crystals grow and thicken, gradually disappears. This is to say that this highly functional protein matrix conducts its own constructive deconstruction at the same time as it gives rise to the enamel tissue. Evangelical musings that remind us of how "except a corn of wheat fall into the ground and die, it abideth alone: but if it die, it bringeth forth much fruit" (John 12:24), and Juliet Capulet's ecstatically exclaiming from her Veronese balcony, "My bounty is as boundless as the sea, my love as deep; the more I give to thee, the more I have, for both are infinite" [9], immediately come to mind, again to tell us that having in life is reserved only for those who learn how to selflessly give. A sage in us may tell us in an even more poetic manner that, paradoxically, only when we give all that we have in eruptions of love for life around us do we truly build the shine of our spirits, and only when we give away these inner treasures to such an extent that our aim is to reach a perfect poorness in spirit do we reach stardom in the eyes of the Heavens.

3. THE BENEFITS OF METAPHOR IN THE CLASSROOM WHOSE SPACE IS EVERYWHERE

Benefits of the usage of such and similar metaphoric connections during teaching are immense. First of all, the only way we could understand a concept is through analogy. We could enrich our knowledge by logical means, but to grasp a new relationship an analogy is required. Hence a sense of enlightenment arising as the result of imaginative analogical thought process. The second most important thing is that metaphors facilitate the learning process by making the taught concepts stick to the students' heads more firmly. By offering metaphorical explanations, one makes sure that the principle pointed at will stay much more firmly anchored to the depths of the students' minds than it would have been achieved by ordinary descriptions in plain words. As it is shown in Fig. 2, grasping abstract concepts in particular benefits from the pairing of their description with appropriate picturesque analogies, whereas this effect need not be always quantitatively evaluable for concrete ideas that are tied to specific imageries in the first place.

Paradoxically but true, diverting every once in a while from the main content of a presentation to tell a metaphor of the scientific subjects taught or merely discoursed on keeps the listeners awake and makes them more receptive than it is being accomplished by linearly proceeding treatises that never stray from the topic. This may be a natural consequence of the fact that an essential element of all intellectual adventures in which we participate is a constant escape from myriads of blind spots that multiply in our views as soon as we settle in them. Perception of a relationship from a new angle is easily achieved through a metaphorical description, which aids in stepping away from the stances being held and avoiding the blind spots in which our intellect may be trapped if it only sees the relationship from a single angle. Babies easily get bored of resting stilly in a single place, requiring constant movement to be kept tranquil, and if this observation tells us something through its quirky metaphor, it is that our cognitive makeup requires incessant adventurous movement back and forth in relation to the subjects of its focus to ensure and sustain optimal learning conditions.

Demonstrating how a microscopic relationship is presentable by substituting its atomic actors with human ones thus greatly aids the learning process. After all, even when we imagine these ultrafine, atomic and molecular events, we do it in terms of geometrical forms which we learned to recognize by observing daily objects. Therefore, I smiled in sympathy when I noticed an Italian scientific duo beginning their review article on self-assembly phenomena at the molecular scale by referring to the relevance of the social principles Plato derived in The Republic to governing "the controlled assembly of fundamental molecular modules" [11]. And if barefooted and ecstatic Richard Feynman could compare diffusing atoms with mingling partiers at one of his lectures, why could not anyone else indulge in similarly inspiring analogies between any two domains of the physical reality? For, impressive metaphors lie at the heart of the systemic approach to understanding and developing human knowledge, springing forth from a belief that "reality is a slippery fish that can be caught only with the hook of a metaphor" [12].

4. HUMAN BRAIN AS A BIOLOGICAL DEVICE FOR COMPUTATION OF METAPHORS

Many are indications that any common reasoning or sensing involves the use of analogies. For example, each time an impression coming from the outer world invokes in us an association of a pleasant or unpleasant memory, analogies and not the strict causal chains of logic are involved. Experiencing an artistic piece, whether it is a painting, a musical or literary work, is most enlivening when the perceived relationships are seen as metaphors of relationships existing in our very lives. Each time we become deeply moved or driven to tears by a work of art, it is because we have found striking metaphorical parallels between the given artistic piece and our visions of the world. Hence the impression that the most powerful artists are also immaculate storytellers who know it all about our lives and who have somehow made the encounters with their works an intimate infusion of our spirit with an inspirational energy that could guide us towards more inventive destinations in our daily lives. What is more, if analyzed deeply enough, each intelligible and truly meaningful impression could be seen as composed of a blend of logical and analogical threads of reasoning.

A radical thesis that could be proposed at this point is that human brain actually presents a biological device for computing metaphors, and that exactly this capability thereof made it superior compared to the remaining living species. Neuroscientists may then tell us that this is why fusiform gyrus, the area of the brain located as a crossroad between sections of the brain that regulate vision, hearing and touch, where the synaesthetic, analogical thought, which all the creative minds all the world over have been gifted with, is thought to be churned out, is eight times bigger than in other higher primates[13]. Intensification of analogical thought in the sphere of our psyche can thus be seen as occurring in parallel with our rise, as humans, along the evolutionary ladder and distancing from our animalistic predecessors, while approaching our supermannish successors. For, the ability to reflect on one's own thoughts and perceptions, being the basis of creative thinking, is the privilege of humans in the animal kingdom, and it can be said to stand at the root of analogical reasoning, which is based on finding parallels between relationships drawn at different levels in the microcosm of our thoughts. It is worthwhile to notice also that exceptional reliance on analogical inferences is the trait of not only genii, but of madmen too, that is, of people who randomly and nonsensically correlate distant concepts and ideas, but such is the nature of life: every sword in it is a double-edged one.

5. DISCOVERY PROCESS OWES A MILLION TO METAPHORS TOO

So we see that every new concept can be grasped only through an analogy. Consequently, the discovery of new ideas can be thought of as happening exclusively along the corridors of analogical, metaphorical thought. Albert Einstein, for instance, realized that the physical qualities of a system in relation to certain observational frame should be modified as the system approaches the speed of light while he was riding on a Bern tram and moving away from the city's clock tower[14]. Descartes came to the idea of Cartesian coordinates as he watched flies buzzing in a top corner of his room[15]. Newton was inspired by an apple falling from a tree to concoct the law of gravity[16], while Harold Rosen designed the stable trajectory of geostationary satellites after the way quarterbacks spin the passing ball in his most beloved sport[17]. Archimedes realized that the volume of an irregular object could be calculated by measuring the volume of water displaced when the object is submerged in water while he was taking a bath. Tesla strolled with his fitness trainer through a Budapest park with a verse from Goethe's Faust stuck in his head, portraying the poet soaring high to catch the Sun setting over the horizon. In one moment he glimpsed the sundown through the branches; with the Sun descending before him and him ascending to it in his thoughts, the idea of the alternate current motor was born[18]. All of this tentatively confirms Henri Poincaré's statement that "pure logic could never create anything novel; nor any science would be able to arise out of it only'[19].

Sometimes, of course, our scientific models bluntly resemble the real-life relationships from which they were derived by analogy and the most famous example, I believe, is the Bohr-Rutherford model of atom. This model was proposed in the times when a mess of concurrent models was used to explain the atomic behavior – the cubic model, the plum-pudding model, and the Saturn rings model. As if being guided by the metaphor of the Sun and the unity that it represents, Rutherford and Bohr placed the Sun in the nucleus of their vision of the atom and thus united all of the preceding models around a single one. Eventually, they proved it to be more valid than any model proposed before. Thus, on the wings of a metaphor, the Sun can be said to have shown the way for humanity to understand and become friendly with little atoms and use them for the benefit of all. For, the Bohr-Rutherford model depicted electrons as circling around the nucleus just as the planets circle around the Sun. The only difference was in the nature of forces that supported this continuous movement. Whereas in case of the solar system the balance between the centrifugal force that tends to drive the revolving planets away from the Sun and gravity that tends to bring them closer to it is responsible for the planetary circling, in case of the atom gravity was hypothetically replaced by the electrostatic attraction. A subsequent enigma was how come the electrons stay in stable orbits when the calculated equilibration of the forces predicted their slow descending into the Sun, that is, the center of the atom. To explain this, Erwin Schrödinger picked on the major improvement that Bohr introduced compared to Rutherford's model, i.e., quantization of the atomic energy levels, and represented them as different harmonic modes of vibration of a guitar string. He resorted to yet another metaphor - atom as a source of music – and the rest was history.

6. ART AND SCIENCE BROUGHT TOGETHER WITH THE METAPHORIC THREAD

Asked by a disciple about the supposedly unprecedented enormousness of his master's, Confucius' knowledge, Confucius replied: "I do not know much. All I know is like one thread. But that thread connects to all the others". From the perspective presented here, analogical, systemic thought could be hypothesized to present this thread that connects to all the other threads in the world. The infinite metaphoric richness of systems that are at the focus of our scientific inquiry implies that the most miniscule subjects of our research, such as the aforementioned tooth enamel, hide the keys to insights of infinitely greater relevancies. Hence the image of a pyramid as the geometric symbol of human quest for knowledge, insinuating that whatever the brick from the bottom that we start our journey from, the peak of human knowledge, offering a divinest view of reality, could always be reached. With the most famous pyramids residing in deserts, I bring to mind the case of the Atacama Desert, the driest one on Earth, with a landscape as dull and lifeless as it could be, where some rocks have lain still for dozens of millions of years. Despite that, it has provided sources of insight into the tectonic plate subduction phenomena, the chronology of continental drifts and ice ages and, when green microbes were found in halite minerals on its surface, into the general origins of terrestrial life on our planet and elsewhere in the Universe[20]. So should we be sure that even the least interesting subjects of scientific inquiry always conceal an infinite number of gates through which we could enter the road of understanding every single aspect of not only the scientific field to which the given subject belongs, but of the entirety of human experience too. Conversely, an archeologist on a mission to pinpoint the true location of Atlantis did not only spend time probing kauri forests in New Zealand, examining canals around Niagara Falls, walking along the rims of the craters of Mounts Peleé and St. Helens, sailing and diving across the Aegean, surveying Egyptian pyramids along the river Nile and inspecting the ocean rocks around Pillars of Hercules, but he also claimed that "we must explore Irish peat bogs and the Greenland ice cap, learn everything we can about pine trees in California and, of course, study Cretan and Egyptian pottery styles" [21], and the same principle that instructs us to look literally everywhere, with an infinite curiosity and open-mindedness, in order to deepen our focus on the pieces of reality that present the subjects of our research applies to all other scientific disciplines.

By correlating things through metaphors, by placing one car after another in the endless train of associations, we may find connections between any two objects, qualities or events in life. In fact, if we looked at the world long enough through the telescope of analogies, everything would start to appear as connected to everything else. "The stories about snails and trees are also stories about you and me" [22], says the daughter in one of Gregory Bateson's metalogues, in the enlightening moment of understanding that any relationship presented as part of any scheme of things, of any model or a narrative could be metaphorically copied onto any other relationship in Nature, if only we are inventive enough to avoid merely linearly connecting insights and ideas along a single, logical plane, arranging them instead on top of one another and linking via invisible threads of analogical parallels.

By drawing imaginative metaphorical threads between scientific imagery and real life, we also bring science and art closer together, cross-fertilizing the two and putting an end to the modern age dominated by (i) uninspiring scientists unable to release their minds to the free flights of fancy that would launch them to the spheres of unprecedentedly progressive thought, and (ii) Dadaistic artists deprived of the will to analytically subject the world of arts to scrutiny and find meaningful niche for their expressions therein. After all, ever since I plunged into the allures of the Glass Beads Game and decided to dedicate my life to reanimating the balance between science and arts in every aspect of the world as I had known it, I have tried my best to infuse the overly chaotic world of arts with logic and rationality, as well as to break apart the conceptual and expressional rigidness of the modern science by blending it with the highly aesthetic forms of expression. What has moved me in this perhaps profoundest interdisciplinary endeavor out there was the belief that such intromission of sciences and arts could make science more elating for the human spirit and presentable in less cold and more heartwarmingly inspiring and poetic fashion thereby, as well as make arts less Dadaistically impulsive or coldly conceptual and more rigorously studious and analytical, again not in a brainy and emotively detached manner, but in a way that brings about illuminative complementation of rational and intuitive powers of our psyches and creates the fabulous concoction that crowns our creativity with the epithet of divine. Science today has been sustained on the hands of its exceptional insistence on logic and analyticity, although on the account of depreciating the importance of intuition, of spontaneously sprouting feelings, of blissful emotions, prayerfulness and the artistic sense. However, all of the latter could be seen as crucial drives for conducting brilliant scientific projects with brilliance. If neglected, an immense toll would be taken away from the heart of the enterprise of science, unavoidably ruining its excellence and inspirational character in the long run. Scientific tradition would thus turn into coldblooded entrepreneurial machinery that serves the purpose of building intellectual robots for the future, generations of people who will blindly follow its programmatic projection of progress, without ever questioning its foundations. Or, as Michael Polanyi pointed out, “The professional standards of science must impose a framework of discipline and at the same time encourage rebellion against it” [23].

7. RETURN TO THE BEGINNINGS WITH THE KEY IN OUR HANDS

The initial statement of this discourse was the announcement of deadness of the spirit of materials science and its scientists of the day. Since I strongly believe that a complete poetic or philosophical work should mirror the Orphic journey to the underworld, not stopping at the part of being lost, but continuing all the way to the part of being found too, I know that a key must exist to help us return to the daylight from these dark forests of human soul at which we find ourselves now. Or, to revert to Conrad’s Heart of Darkness, journeys into the hearts of darkness are valuable only insofar as we return back to the bountiful and sunny seashores from which we had set off to our adventure, lest we become an epitome of Mistah Kurtz. The question that I wish to elaborate at the end is this: “How could we revive this slumbering spirit and enliven it again”? We learned at first that we are dead because it is in the nature of our cognition to metaphorically comprehend reality and thus reflect what it sees across all cognitive levels and facets of personality. The prosaic nature of the way materials science is being presented today in classrooms and conferences is thus directly reflected in the prosaic nature of the spirits of materials scientists who are intimately connected with this science on day-to-day basis. And, as the old Buddhist proverb tells us, the same key unlocks the doors of Heavens and Hell. No other guiding star would we need at this point.

Hence, as the problem lies in the metaphor, the solution must lie in it too. Therefore, the answer to this question is the following: "We will become alive again when we recognize life in what appears to be dead". I will pick now a little stone from the ground and tell you that only when we learn to see in millions of physical processes that occur in it millions of metaphors of profound ethical and aesthetical significance for our lives will our spirits revive again. Thirteen examples of such metaphors by the wonder of which we may relearn how to "see a world in a grain of sand" [24] I will list here.

7.1 Like all things in life, the form of a crystal is defined by both intrinsic and environmental factors

Crystals have a natural tendency to grow such that their visible faces correspond to the most energetically stable atomic planes in the crystal lattice, but at the same time the environmental factors add up their own influence to the physicochemical conditions of the crystal growth. Consequently, supersaturation level in the medium surrounding the growing crystals defines the crystal growth rate and the surface topography (i.e., in general, relatively low levels of supersaturation produce smoother surfaces), but the latter are also dependent on the initial properties of the crystal surface (that is, whether it was flat, kinked and/or stepped to start with). The origins of shape, symmetry and all the tiny ridges on the surface of the pebble we just picked from the ground can be thus traced back to its insides as much as to its outsides. For example, crystals of the same compound might have a completely different appearance as a result of their growth under different conditions. That they can also behave differently is demonstrated in Fig. 3, where we see how a chemically identical compound, in this case indium, exhibits a thoroughly different function of the melting point on the particle size depending on the method of synthesis: ball-milling or melt-spinning. In contrast, two minerals may have completely different compositions and still look almost indistinguishable because of the similarity in the environment of their formation. Igneous rocks are, for example, notorious for being often virtually indistinguishable from one another by visual means owing to their rapid formation from incandescent and molten lava. This flies us over straight to the doorstep of the concept of co-creation, according to which both the subject and its environment are responsible for co-creating every single detail of the subject's experience[25]. The importance of this principle is such that one could consider it as the metaphysical basis of all conceivable epistemologies and ontologies, with the two, the philosophy of human knowledge and the philosophy of human being, being seeable through its eyes as inextricably tied to one another. And note how quickly a single look at a little pebble revealed to us the secrets lying hidden in the most arcane atria in the pantheons of human knowledge, all with the help of an analogy connecting empirical with abstract, particular with systemic, physical with philosophical.

7.2. Given the same content, internal ordering can sometimes make a difference between sturdy and fluffy

This can be exemplified by graphite and diamond, two compounds made of carbon atoms only, but of very different physical appearance, crystal structure and corresponding mechanical properties. Whereas diamond, the strongest naturally occurring material, is a brilliant insulator and the most popular gemstone over which wars have been waged for centuries, graphite is cheap, soft, dark and conductive. All this is due to the fact that whereas hexagonal graphite layers easily slide past one another in [hk0] directions due to comparatively weak van der Waals bonds between the layers, all carbon atoms in diamond are covalently bound, which contributes to its exceptional strength that secured its place at the very top of the Mohs scale. This is all to say that not what one has or start with, but what kinds of connections one builds between the elementary entities in possession defines how great the outcomes of these creative efforts will be. Also, although most people would prefer to associate themselves with strong and lustrous diamonds, the synonyms for perfection in the materials science realm, there are still rare, insightful ones who would rather want to be the epitomes of opaque, earthlike looking graphite, having recognized that whereas diamond mostly cuts through things due to its superior strength, graphite enables one to leave marks on worldly things, softly, without hurting them. Like the "heart" of a pencil made of graphite that crumbles away when slid against the paper owing to the weak van der Waals bonds in-between the hexagonal layers, so may soft and essentially weak, not stony, hearts, filled with empathy and bleeding with love, be those that leave lasting impressions on the world and change it for better. When I compared acids to romantic couples a few paragraphs earlier, some of you might have already begun to wonder if strength is actually weakness and weakness is strength, but now we see in an even clearer light that every form of strength is a weakness too, while every weakness could be turned into strength.

7.3. The past habits of crystal growth influence its future growth

What we do today sets the habit for our future actions, and the same effect exists in the world of crystals. If a crystal grew at a relatively high rate for some time in a highly supersaturated environment, the later growth of the crystal under a lower supersaturation will proceed at a different rate compared to a crystal that had been kept in a lower supersaturation environment all of the time[27]. This is normally explained by the different roughness of the crystal surface. First of all, the faster the crystals grow, the more imperfect their surfaces will be. Crystals grown first in highly supersaturated media will thus have a rougher surface than those grown in lowly supersaturated solutions. Subsequent growth in the solution of the same supersaturation will proceed faster for the former, topologically rougher crystals, whereas the latter, smoother ones with an identical composition will grow slower or may even remain unchanged under the same conditions (Fig. 4). Likewise, the same type and amount of external impressions can sometimes leave one person thoroughly untouched and the other one drowning in waves of emotions. Hence, just like the habit of crystal growth influences its future growth, the habits of our thinking and judging about the world, deeply ingrained within us, outline the way for the future incorporation of impressions within ourselves. This may be an implicit sign that patiently and persistently cultivated goodness in our mind and heart always pays off, as it spontaneously predisposes us to benefit from the environmental stimuli exerted on us.

7.4 In the world of crystals, growing fast does not pay off

Crystal faces that grow rapidly get to slowly disappear from the crystal surface. Such is the case of the growth of a hexagonal unit cell (Fig. 5). A faster growing plane, clinched between a pair of slower growing ones eventually turns into an edge of a cubic crystalline particle[28]. In case of a cubic unit cell, the effect is somewhat milder. Any faster growth along a single axis of growth would yield elongated, rod-shaped particles on which the fastest growing face would still be present, although in a diminished proportion compared to the crystal planes growing slowly. The ethical meaning of this observation suggests that slowness and patience are qualities that yield long-lasting products of knowledge, whereas whatever grows fast vanishes fast as well. Or, as Nietzsche's Zarathustra taught, "Slow is the experience of all deep fountains: long they have to wait until they know what hath fallen into their depths" [29], echoing a century and a half older musings by Alexander Pope: 'Some people will never learn anything because they understand everything too soon' [30].

7.5. Precipitation is an infinitely proceeding reaction

As it was shown in the mid-19th Century by Guldberg and Waage[31] during their pioneering research on the kinetics of crystal growth phenomena, an equilibrium involving a crystal immersed in a solution implies not a constant and unchanging existence of the solid material in the medium from which it was precipitated, but a continuous process of dissolution and re-precipitation. For this reason, used in most chemical balance equations is neither an arrow representing a unidirectional transformation (→) nor a simple sign of equality standing for static equilibrium (=), but a bidirectional arrow coupled to the equals sign (⥦), signifying a constant exchange of mass and energy along the interface of phases in equilibrium. The same principle undoubtedly applies to the dynamic nature of our beings that constantly dissipate their essence in the wind and yet continuously reintegrate and recreate themselves, thus becoming new creatures at every moment of their lives. Every interface is therefore dynamical in nature. Even when two beings stand next to one another and seemingly exchange nothing, be sure that something is always being transmitted.

7.6. Finite crystal lattice vibrations exist even at absolute zero

Fig. 6 illustrates this effect, which could be also described by saying that all is music, music that never stops. Even as we stand in the midst of the most barren and hush landscape imaginable, in perfect stillness, we could try to feel the musical sensations that encompass the entire Universe because everything around and within us, from trillions of cells with their feedback loops that act as internal clocks, to rhythmical patterns that harmonize biochemical processes occurring inside of them, to thousands of moles of atoms in us, rotating, oscillating, twisting, turning, spinning and surfing through space according to precise quantum beats, incessantly creates the music of life. "If our eyes were more perfect, we would see the atoms sing" [32] says the MIT professor of physics and the Nobel Laureate, Frank Wilczek, and continues his musings over the musical, hearable and harmonic nature of every piece of reality by stating that "a race of beings who had this sort of direct experience would no doubt include a high proportion of poets and atomic scientists". By saying this, he gently touched the roots of the tree of human knowledge where scientific analyticity and artistic sensitivity are inseparably entwined, just as plant roots or the rose around the briar are.

7.7. Phase transitions proceed with the initial energy expense

As shown in Fig. 7, the free energy of a crystallization embryo (ΔG_n), being the sum of two energy terms, surface free energy and bulk free energy, initially unfavorably increases with an increase in its size. Only after a critical size, n_c, is reached does the crystal growth become energetically favorable. This is to say that crystallization of new knowledge is similarly entailed by hardships, as it requires investment of work and does not proceed spontaneously at all. And this is, remember, in spite of the fact that when the solution is supersaturated enough, the phase transition on the global scale will proceed spontaneously. The relevancy of this effect could be easily transposed to any other physical domain. Take, for instance, the process of getting acquainted with magnificent pieces of art. Our first encounters with them will exert a whole lot of mental strain on us, as if requiring an immense energy hill to be crossed, such as that conquered by a crystallization nucleus that surpassed the critical size. Only after we become familiar with these artistic pieces can we use them as boosters of spiritual integrity and enkindlers of intellectual ennoblement. It is as if knowing them requires climbing up an energy hill, from the top of which we would be able to clearly see them in their entirety, enjoy the gorgeous view and slide down in joy and satisfaction when needed. In life, likewise, it is colossal mountains and hills that we ought to climb at while constructively absorbing stress, using it as a lift and thus moving against our tendency to drop lifeless at the mountain base. It is for this reason that the Freudian emphasis on constant elimination of tensions within our minds and bodies as well as on relaxation from stress rather than on its constructive assimilation can be criticized for mediocrity-fostering ideals. For, whether we consider the evolution of life from protozoa and cyanobacteria, of novel ideas that endow humankind or of enticing expressions and moves, including those of a child learning how to walk, tripping and falling and putting a “star” into every new “starting over”, as spoken word poet Sarah Kay had it[33], all the while determinedly working against the law of gravity that pulls him down, they are all based on breaking the behavioral standards of normality, habitualness and ordinariness as well as the physical laws of thermodynamics and inertia superimposed on them. This is also to remind us that science benefits most from thinking that resists to inertly follow paradigmatic streams, that countervails the trendiness and that clashes freely with the opinion of the majority, treasuring in its heart the idea that conformity equals regression in the big frame of the evolution of our knowledge.

7.8. Crystallization occurs at the interface between the coasts of order and the sea of disorder

The metaphoric nature of thinking implies the existence of a pair of levels at which our reflections alternately occur. At any given moment, one of them holds a firmly presupposed or verified idea, whereas the other one rapidly shuffles images and connections in search of a consistent analogy. And so these two levels stimulate each other in search of new ideas. As such, the thinking process could be said to neatly resemble the crystallization process. As in the thinking process, two phases, one of which is liquid and one of which is solid, interact during crystallization. The randomly arranged substrate of the thought process corresponds to the liquid phase of the crystallization process, whereas the preexistent body of knowledge composed of a network of interlocked premises is akin to the crystallization nucleus on which the crystal growth occurs. The elements of order and disorder are thus both present and well balanced during creative thinking and the same principle applies to any other process in the course of which something original and inventive is being born. For, ‘only randomness can give rise to novelties’[34] as Ross Ashby, one of the founders of the field of cybernetics, observed. Another call implicit in this metaphor is for the scientists to stand at the seashore of knowledge, not in the bulk of their dogmatically reinforced ideas, but out there where the waves of the ocean of the unseen, unformed and undiscovered crash against the coast of the well affirmed and already crystallized body of knowledge. But why not leaving the land behind and setting off to an open sea for good, you may wonder. It is because questions can arise only upon a network of presupposed answers to some other questions in life. Consequently, a perfect, absolute wonder, questioning and doubt about everything, is utopian. It cannot exist because only by resting on some firms coasts of knowledge could we wonder over the mysterious oceanic streams that Nature abounds with. It is therefore that I am free to conclude that a scientist and a profound thinker is always a dreamer on the seashore of human knowledge. Or, as Isaac Newton noted down, “I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me” [35].

7.9. Crystallization occurs sequentially, in stages

Ostwald-Lussac’s rule (Fig. 8) tells us that whenever atoms of a compound we intend to crystallize can adopt multiple spatial arrangements in space in the solid form, the first phase to precipitate from a solution will not be the most stable one. Instead, the least stable and the most soluble phase will be the first to form. Either its transformation to a more stable phase or subsequent precipitation of the latter on top of it ensues. In his epic chemistry book, On Growth and Form, D’Arcy Thompson expanded this principle by stating that “in accordance with a rule first recognized by Ostwald, when a substance begins to separate from a solution, so making its first appearance as a new phase, it always makes its appearance first as a liquid”[36]. In such a way, he demonstrated a simple entropic argument dictating that the first solid phase to crystallize at an interface with a liquid has to be amorphous, the most structurally similar to the liquid, intrinsically disordered phase from which it originated. Only subsequently will these amorphous intermediates transform into a crystalline phase and that either by a non-diffusional, martensitic mechanism involving internal reordering of atoms or molecules or by following a diffusional, dissolution/reprecipitation mechanism. What this extended principle suggests is that whatever the creative act in question, the first steps ought to carried out lightly and unpretentiously, as if we are a liquid in quiescent and gentle flow. Brilliant performers often begin their acts akin to a camouflaged animal, perfectly blended with its surrounding, as disorderly and awkwardly as the Little Tramp masked as Adolf Hitler in the last scene of the Great Dictator, gradually growing in the intensity of their glow all until they eventually eclipse all else with the brightness of their burning blaze. By doing so, they, perhaps unknowingly, reflect the way first crystallization nuclei form from a mishmash of a fluid and amorphous solid state.

7.10. Striving for perfection almost invariably leads to failure

For many years, bone regeneration specialists deemed that the stronger the material used as an *in vivo* substitute for a damaged hard tissue, the better. Then, it was discovered that applying metals as bone substitutes is unfavorable exactly because of their superior mechanical properties. Once implanted in the body, metals tend to absorb most of the mechanical stimuli that the surrounding tissue is subjected to. Just as one’s living in a perfectly sterile environment slowly puts one’s immune system to sleep and makes one less resilient to intruding species, this stress-shielding effect induces weakening, not strengthening of the surrounding bone. As the mechanical forces are directed away from it, this bone adjacent to the implant becomes eventually resorbed, threatening the collapse of the entire biomechanical structure[38]. This insight may be complemented by the many times observed necessity for a biomaterial in contact with cells to possess a rough surface, for only as such can the conditions for an optimal cell attachment be achieved[39]. For this reason, titanium is subjected to sandblasting and etching prior to implantation[40] (Fig. 9). The material is thus endowed with surface roughness, which makes it seemingly less perfect at the first sight, although it leads to a more optimal integration with the organism in the long run, as confirmed in numerous studies[41,42]. The creation of partly defective structures with the purpose of boosting their bioactivity has thus grown into a mainstream approach in the field of tissue engineering[43]..Additionally, not only cells, but small molecules too are best adsorbed on rough surfaces, as demonstrable by the absence of adsorption of carbon monoxide on atomically smooth gold[44] or by the higher hydrogen adsorption capacity of topologically defective carbon crystals as opposed to perfectly atomically ordered ones[45], all of which is, of course, in agreement with the Gibbs isotherm that assumes a direct proportionality between the surface energy and the quantity of the adsorbed gas. This example brings to mind the ancient Hawaiian aborigines' decision to assign the name *a'ā*, that is, the first letter of the alphabet repeated twice, a symbol of the beginning of it all, not to smooth and flat lava known as *pāhoehoe*, but to clunky and jagged lava stones. For, it is from the latter that life in the form of flowers and trees began to sprout before spreading over the entirety of these Pacific islands, once bare like the surface of the Moon, but now luscious and bursting with biological diversities. Hence, from biomaterials to conventional catalysts to volcanic rocks, surface imperfections are vital for the optimal functionality and proper performance of these materials to be maintained. All this is meant to prompt us to reckon all those magical moments in life that presented themselves to teach us that to be imperfect is to be perfect and the other way around.

7.11. Bond stiffness decreases in parallel with the particle size

In the atomic world, the more neighbors one has, the lesser the flexibility of one's movements around a given bond and, conversely, the greater the stiffness of one's position in the crystal lattice. This is illustrated in Fig. 10, which shows a sudden drop in Debye and Einstein temperatures, directly proportional to the bond stiffness, when the size of platinum nanoparticles is decreased from 12 to 2 nm. Naturally, like all other physical observations, this one carries a connotation relevant for the social realm too. Namely, just as a bond between two atoms in a crystal is stiffer when they belong to a very large structure, so will two creatures holding hands and trying to dance in a room full of people, with dozens of eyes looking at them in the same way as predators lurk their prey, naturally be less relaxed and stiffer in their movements. But should you decrease gradually the number of these neighboring eyes, the looseness of the performance of the two dancers, atomic and human alike, would start to increase, all until it reaches its maximum at the stage when they remain alone and able to literally dance as if no one is watching.

7.12. The windiest, longest road is often shorter than the straightest path

At least so is implicated by the effect of catalysis. Namely, as could be seen from Fig. 11, the two hypothetic reactants, A and B, in the reaction A + B = AB have quite a hill, the height of which equals the reaction's activation energy, to cross, but the path seems more linear and straightforward than the catalyzed alternative. That is, they just need to find each other, touch and voila, the rest will unwind by itself. The alternative seems more complicated and supposedly longer to take, but, in reality, it will bring them to the very same destination faster and with far less effort on their behalves. Per that alternative, one of the reactants is to turn away from his partner and, surprisingly, grab another entity by the hand, be it an inanimate surface or a creature, simpler or more complex than itself, and bind to it temporarily. An AK complex is thus formed and B is left seemingly by itself for good. But K, the catalyst, has a plan in its pocket and, when it pulls this magic trick, in the blink of an eye A and B will be brought together, while it, itself, will be riding off into the sunset, all alone, as all saints in life do.

This teaches us that winding roads are those that will startlingly bring us to the journey's end in a far more elegant fashion than if we were to follow a most direct route. Also, temporarily leaving behind those with whom we should unite in the end is a prerequisite for our arriving at their embrace in the fastest possible fashion. The take-home point of this effect may also be this: when an obstacle comes across our path, insurmountable, as it may seem at times, we should seek an entity to interact with, for it will magically open the road bypassing it, with multiple, though smaller and more easily navigable hills, and, magically, deliver us straight to our destination, which would have taken far longer to reach had we started to walk directly towards it or if we had sought a detour all alone, staying in the bubble of our own self all of the time.

7.13 Impurities and irregularities can be the sources of something great

Intentional introduction of impurities, irregularities or functionless components so as to make a material less pure and perfect often results in its greater reactivity and a fascinating functional upgrade. An example derived directly from my research on magnetic nanoparticles is that of nickel-zinc ferrites[47]: namely, with the addition of diamagnetic zinc ions to the crystal lattice of nickel ferrite, which comprises two magnetic cations, divalent nickel and trivalent iron, the magnetic moment of the compound surprisingly increases and reaches a maximum at approximately 1:1 molar ratio of zinc-to-nickel (Fig. 12a)[48]. This peculiar effect is explained by the ability of Zn^{2+} ions to replace Fe^{3+} ions from the tetrahedral (so-called A) sites of the inverse spinel structure of nickel ferrite and thus diminish the compensation of the superexchange, antiferromagnetic coupling of the magnetic moments of Fe^{3+} ions positioned on the A sites and Fe^{3+} and Ni^{2+} ions resting on the octahedral (so-called B) sites of the crystal lattice[49]. As Fe^{3+} ions are partly pushed over from A to B sites, the effective magnetic moment on the A site decreases, leading to a higher overall magnetic moment of the material; this is so because the latter is directly proportional to the magnetic moment on the B site minus that on the A site. Another illustration of how adding a seemingly useless component into a physical system need not necessarily compromise its functionality, but can actually improve it comes from the doubling of the capacity of magnesium to absorb hydrogen upon the addition of 50 wt% of fully inert, hydrogen-saturated titanium hydride to it, owing to the nucleation-promoting effect of the latter[50]. In fact, practically every nucleation process starts on a foreign surface, be it a gas bubble, container wall, dust particle or some other impurity, where it takes place under considerably more favorable conditions. Here comes the joke that the success of chemistry professors specialized in solid state synthesis could be measured by the versatility of crystallization seeds that they bring into the lab in their beard[51]. And just like chemists introduce active foreign surfaces to promote nucleation of new phases, so do profound thinkers place a single sun of an idea in the center of their minds and let it inspire stars and planets of other thoughts to rotate and align around it.

Another example comes from the fact that surface irregularities, such as kinks, steps or terraces, are those where atoms most easily anchor during crystal growth (Fig. 12b). In contrast, atoms and molecules from solution or gas have a hard time finding sites to attach onto an ideal, perfectly flat surface, and the same principle applies to crystallization of new knowledge. In fact, according to the classical models of crystal growth, which describe the latter as directly related to interface morphology, perfectly flat crystal faces would not grow at all without any surface defects on them[52]. If we take a quick peek now at the basic principles of the science of sintering, we might learn that only the grains with rough, atomically disordered surfaces can exhibit normal growth, during which a unimodal and invariant relative grain size distribution appears over time. Unlike them, grains with faceted, atomically ordered surfaces can exhibit only the inhibited or abnormal growth, during which a rapid growth of a small number of large grains occurs at the expense of the disappearance of a large number of smaller grains[53]. In fact, because the driving force for the sintering of grains with faceted surfaces is higher than that for the sintering of grains with rough surfaces, materials were found, such as barium titanate, for which the sintering process came to a halt before the densification was complete, all as a result of the transition of the grain boundary from the rough to the faceted during annealing[54]. This highlights the essentiality of imperfections on the surface of our knowledge -the surface being composed of relationships that are the direct subjects of our reflections – as they are the starting points for the balanced growth of the crystal of our knowledge. The demerits of dogmatism, certainty and phony self-assurance and the merits of a humble and wondering mind that subjects it all to selfless scrutiny thus become immediately obvious.

Moreover, just as atoms difficultly attach onto perfectly smooth and flat crystal surfaces, exciting acts will also hardly ever be performed on the substrate of our obsession with perfection. Note also that the crystallization process can be divided to many kinetically distinct steps, from the diffusion of atoms through the solution to their attachment onto the crystal surface to incorporation into the crystal lattice, and all of these sub-processes have an energy barrier attributed to it, the highest one of which belongs to dehydration of ions prior to their binding to the surface. What this tells us is that in order to gain something, something else ought to be sacrificed. In order to become a crystal, an alchemical symbol for perfection, the most precious companion of ours, like water molecules are for a hydrated ion joining the crystal surface, has to be set free. Or, as the Little Prince would have said, "The stars are beautiful because of a rose one cannot see" [55].

Finally, the content of this very discourse could be seen as one blasphemous impurity in the materials science universe; out of it, yet, I hope, something wonderful might come out. May it be a grain of sand by which the scientific powers that be will be irritated at first, before they, one bright day, without knowing it, magically, give rise to pearls of brave new visions. Or may it be like that one in a billion atoms that is different from others in pure silicon or quartz, enough to magically transform the material from a dull grain of sand to one capable of becoming a part of a computer or a solar cell, awakening "a little Sun that shall illuminate us, slumbering in the stone", as the Yugoslav poet, Branko Miljković put it in his poem The Sun.

8. CONCLUSION, AND A VISION FOR THE FUTURE

Explicitly outlined in this discourse is the need for a greater pervasion of imaginative analogical thought as a complement of logical inferences throughout the materials science education, which, remember, does not begin or end in the classroom. Rather, every time we communicate our science, we are involuntarily involved in an educational activity, affecting the listeners' methodology and motivation. Implicitly, this work aimed at illustrating that science could be told in poetic ways, with a rich philosophical background on which all empirical approaches stand, without losing any of its exactness or practical significance. Although welfare of science is sustained on pillars of countless nonscientific factors, ranging from philosophy to politics to ethics and economy, familiarity with all of which is badly needed in this era in which overspecialization is valued more than the breadth of knowledge across disciplines, aesthetic explication of scientific ideas on the back of an exciting metaphor can be a glue that holds all these columns that support science and ensure its survival[56, 57, 58, 59, 60, 61] together and prevents the collapse of our scientific selves into blind spots of diminished creativity.

The following thought by Alfred North Whitehead is correspondingly the one I would love to leave you with: "The balance of mind reflected in the union of a passionate interest in the detailed facts with equal devotion to abstract generalization has now become part of the tradition which infects cultivated thought. It is the salt which keeps life sweet" [62]. In order to be this salt of the earth, so rare on this planet now, and share with others the knowledge that inspires through its balanced breadth and fineness, we should learn how to stay afloat and swim gracefully on the surface of things, yet also dive patiently, with great persistence, into the darkest depths of the sea of knowledge where all the precious pearls, treasures of sailboats sunken long ago and the remnants of Atlantis lie hidden. This saying is, thus, like a signpost of vital importance on our educational ways, warning us of the dangers of neglecting the need to balance the analytical and synthetic aspects of thinking. For, the point is neither to have productive but narrow-minded and disgruntled materials scientists nor to have those who are going to have a wonderful time doing science, yielding results that are all but original and practically applicable. Yet, by balancing these two aspects of natural thinking, logical and analogical, systematic and systemic, we could instigate both analytical scrupulousness and synthetic imaginativeness in the generations to come.

For, should the former eclipse the latter, science would become even more robotized, inert and programmatic than it is today. Being different in its realm would be severely punished rather than rewarded, even though novelties can in reality emanate only insofar as creative minds rebel against the old and paradigmatic ways of interpreting reality and swim against the stream of settled ways of thinking, the kind of swimming that only living things can engage in, as G. K. Chesterton would remind us[63]. After all, one of the crucial riddles of the Sphinx posed in front of the current generation of thinkers is how to explain the discrepancy between the nature of the core of scientific research and the manner in which it is being presented nowadays. Namely, on one hand creative scientific endeavors stem from the roots of imaginativeness that in its rebelliousness busts the boundaries of clichéd, standardized and customary thinking and produces surprising innovations as its fruits, while on the other hand the less imaginative and boundary-breaking we are in the way we present scientific results in professional journals or at scientific meetings, the greater the chances that we would receive praise from the peer reviewers who stand as Cerberuses, the demonic gate guardians, in front of our road to recognition and success.

But should the latter prevail, the civilization could be brought to the edge of its collapse because the philosophers would be too many and there would not be anymore those with enough patience and determination to focus onto single subjects of study and discover their petite charms of universal importance. There is no doubt that the most brilliant scientific minds have succeeded in balancing specialization with the breadth of systemic knowledge. For, these two – specialized insight and general knowledge – do not impede, but actually propel each other along the tracks of human creativity. This is because the realizations we come up to by focusing on small details in our scientific explorations metaphorically speak to us about the greater secrets of our lives, of the world and the Universe, whereas these great secrets, applicable to an endless number of various natural systems owing to their systemic nature, help us successfully guide the research of ours at a finer scale.

We have approached the end of this string of ruminations and this is my final confession in it, so come close. I dream of the times when reading a materials science paper will make the scientists cry by touching their hearts in the most poetic of ways. I dream of the times when cold and prosaic practice of the modern day will give way to a more inspiring style of comprehending and doing science. I dream of the times when science would be written free-mindedly, with the writer's wits akin to those impressed on the pages of Jack Kerouac's On the Road, James Joyce's Ulysses or Gertrude Stein's children's stories, overturning the foundations of scientific expression and enriching its semantic essence. I dream of the times when I will recognize a playful and prayerful walk through the gloomy forests and meadows of the province of science in written works that question not only the dull and unimaginative presentational manners that dominate the modern science, but its robotically programmatic empirical foundations too. I dream of the times when every scientific presentation will be crafted so as to simultaneously inspire the reader and convey important knowledge to her. And then, one day, if we continue to journey along this thread that connects science and arts, and even more and beyond, farther than the farthest horizons in our sight, we may arrive at the destination that is called Glass Beads Game, the science and art to the popularization and mastering of which this work has contributed.

In the end, I ought to say that I have just opened my heart as if it is a flower of a kind. That heart is full of beliefs that science could become not more treacherous, but more profound and inspiring by being enshrouded by the veil of poetic philosophizing. The relationship between science and art could be instructive in this sense. For, scientific inventions have helped the multiplication of the products of arts in terms of their quality and quantity alike - think of music, cinematic arts, the art of photography, literature, etc. - while involvement in arts, which some of the greatest scientists from the present and past have attested to, has enabled the boost of the passion and will to discover something great, something from which humanity as a whole would benefit, which is the first step on the road that leads to invaluable scientific findings. The closed loop in which science and arts are found is such that arts invigorate our creativity with their aesthetic powers, leading to ever more sophisticated technological tools that are used for producing ever more captivating artistic expressions, and so forth, so long as the wheel of the progress of our civilization keeps on spinning. If science and art do not stand in each other's ways, but, in fact, enhance the qualities of one another, why couldn't we expect the same from the greater perfusion of poetry and philosophy through the standard scientific courses, technical papers and presentations at conferences?

Still, the wonder continues. Therefore, I advise you not to trust all I have said. This is exactly what I always tell my mentees: the final doctrine is that there is no doctrine to be followed. For, awareness that no one in the world could give us good advices a hundred percent of the time as well as that even the most malicious souls could occasionally, intentionally or not, in a Mephistophelean manner[64] give us an advice worth cordial following, is a vital feature of independent thinkers whose crafting ought to be the ultimate aim of the academic training. Therefore, it is quite possible that I have been biased towards my own poetic sensibility when I conceived the ideals presented here. Maybe it is my upbringing that involved reading poetry and studying ancient philosophy side by side with solving complex atomistic equations, and finding enjoyment in both, that is to be blamed. Maybe all these peculiar views, rejoicing like children over communality, cordiality and warm-heartedness, sprang forth from my cultural background, from Yugoslavia, a motherland that is no more but was a worldly symbol for diversity in unity and inclusion, not exploitation, of the poor countries of the world. Maybe the worldview presented here, appearing so foreign and so intensely disliked by what its holder sees as cold, corporate and materialistic mindsets of the puritanical West that define the scientific mentality of the modern day, is but an intellectual virus that is to be mercilessly eradicated from the face of the Earth. Maybe all these warped views have come to being because my scientific views had been hatched at YUCOMAT conferences where the old guard professors would blend poetry, philosophy and materials science over guitar sounds, sea splashes and wine. Maybe it is a saddening sense of loss for this old, Romantic way of doing science that has moved me to do my best to preserve it in its authentic form in these words, even though they may be outdated by a moonlight mile. Finally, maybe all of this is just a product of a fancy that is wholly out of its mind.

But whatever is the case, if science continues to follow the trend of unimaginative presentations and narrowly limited specializations, it may eventually fall off the cliff and, one by one, the endless colony of followers that comprise the scientific enterprise will drown once and for all in the troubled and torturous waters of dissatisfaction, misery and robotic coldness on some future day. Then, these words may be dug out from the dust by some curious eyes, gingerly held on the palms of their hands, carefully looked at, recognized by their ability to melt one's heart out and brought to light as one of those signs of the times that had been shoved to the ditches by the side of the road by the careless colonies of sheepish followers that constitute the mainstream of the modern science. And the most beautiful things, the cornerstones that the builders cold-bloodedly rejected, as these words have wished to show, will have always resided in the quietest and the most forgotten corners of the cosmos. For, if there is one thing that materials science has implicitly taught us, it is that in the immeasurably small, smaller than the smallest grains of sand, the most beautiful and the most cosmically relevant secrets dwell. And when we come to conclusion that $\cdot \approx \infty$, so to speak, that infinitely small and infinitely infinite flow to and fro one another, the book of science may be able to gently fold its leaves and say a soft goodbye.

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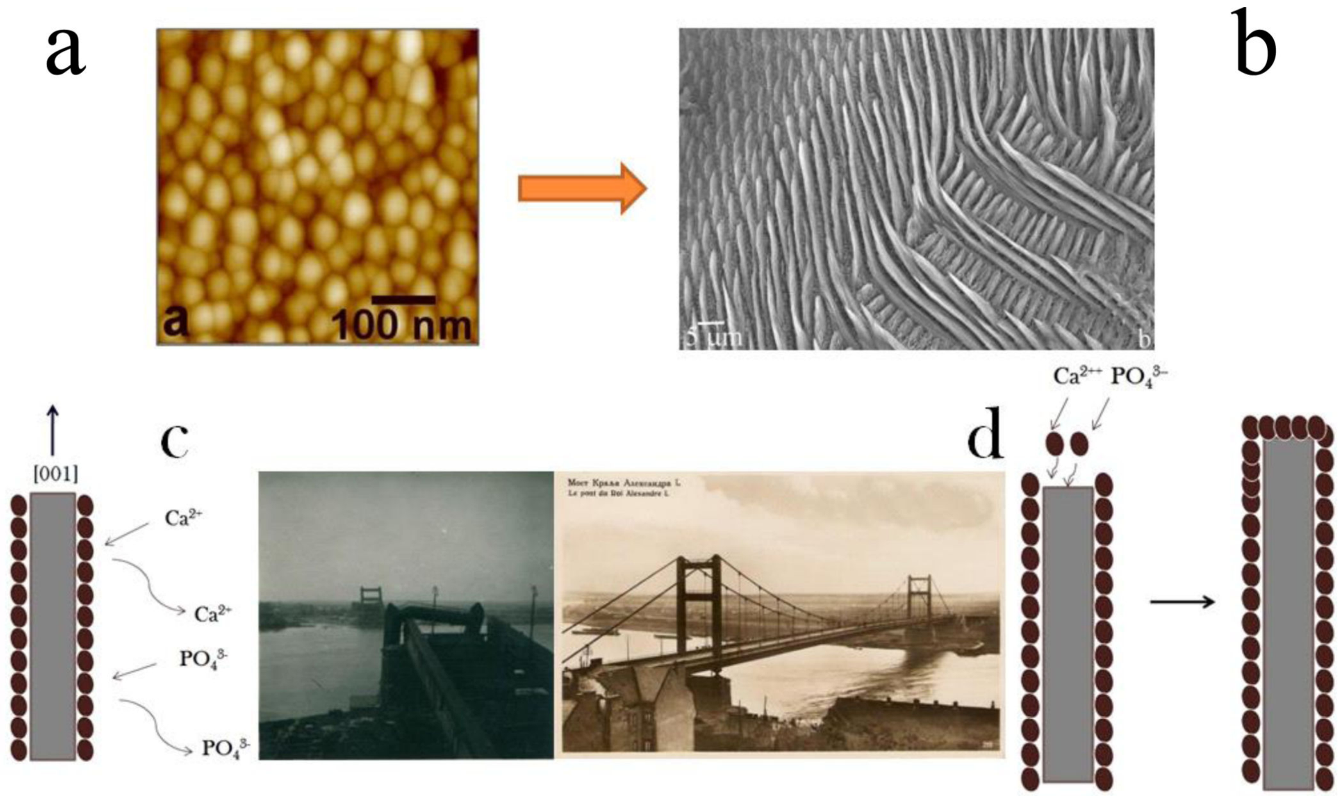


Figure 1.
During the process of amelogenesis, a gel composed of nanosized spherical assemblies of amelogenin (a) serves as a template for the simultaneous construction of apatite fibers with the aspect ratio of 1:10,000 (b) and well-coordinated destruction of their own selves. The old paradigm that stated that the role of these protein nanospheres was to adsorb onto all but (001) crystal faces and block the inflow of incoming calcium and phosphate ions, serving effectively as broken, bombed bridges (c) is now substituted with a new view of the role of these protein aggregates, metaphorically describable by bridges that channel the ionic growth units from the enamel matrix gel to the growing crystalline surface (d). The bridge shown in the image is that of King Alexander's in Belgrade, one of many destroyed ones during the regular ruinations of the city by its various conquerors, which have happened every 30 years or so on average.

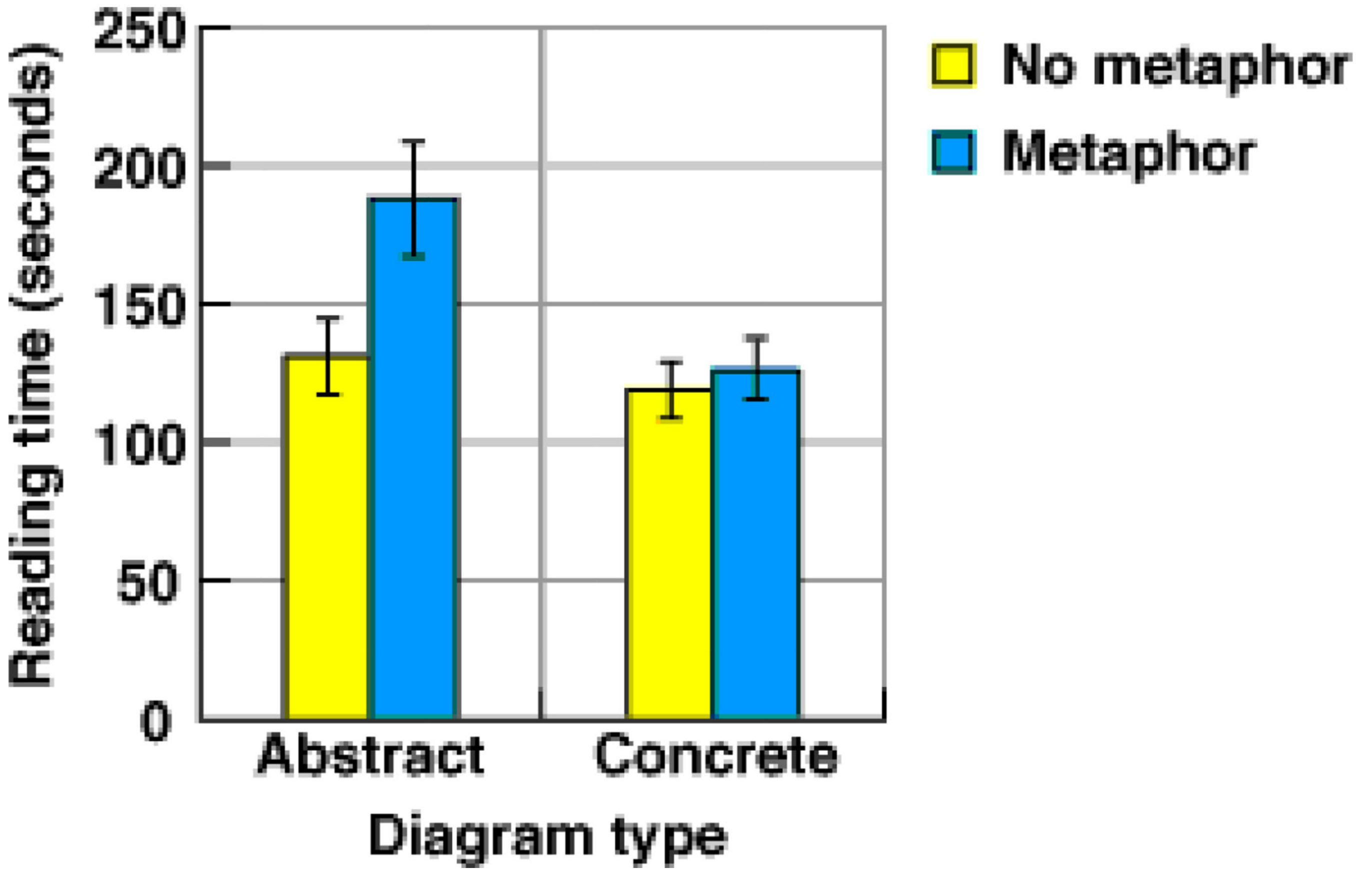


Fig. 2.

Reading time needed to grasp a set of abstract and concrete concepts with and without coupling their descriptions to metaphors. Reprinted with permission from the University of Cambridge[10].

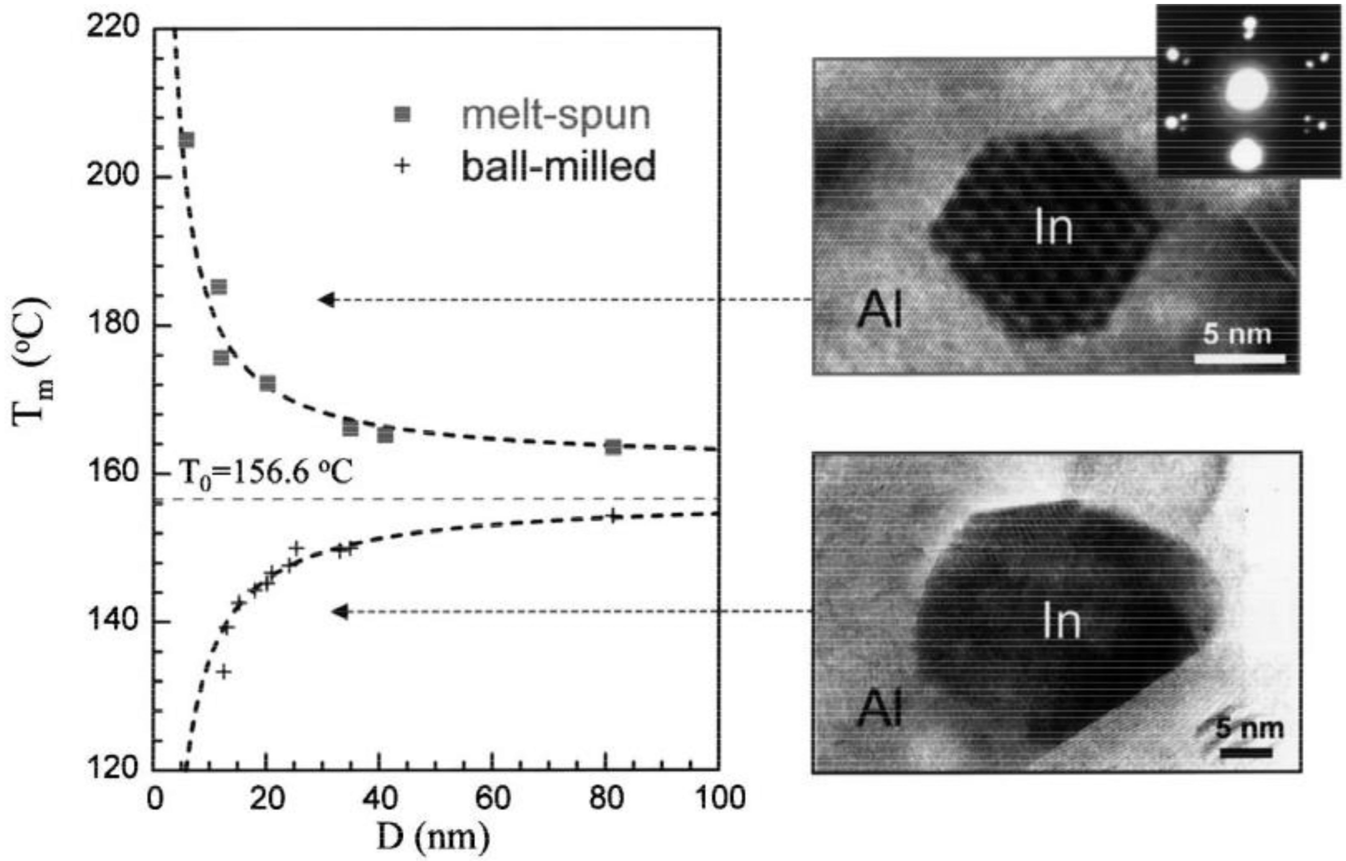


Figure 3.
Melting point of indium embedded in aluminum matrix as a function of indium particle size for two different preparation procedures. Reprinted with permission from Ref. 26.

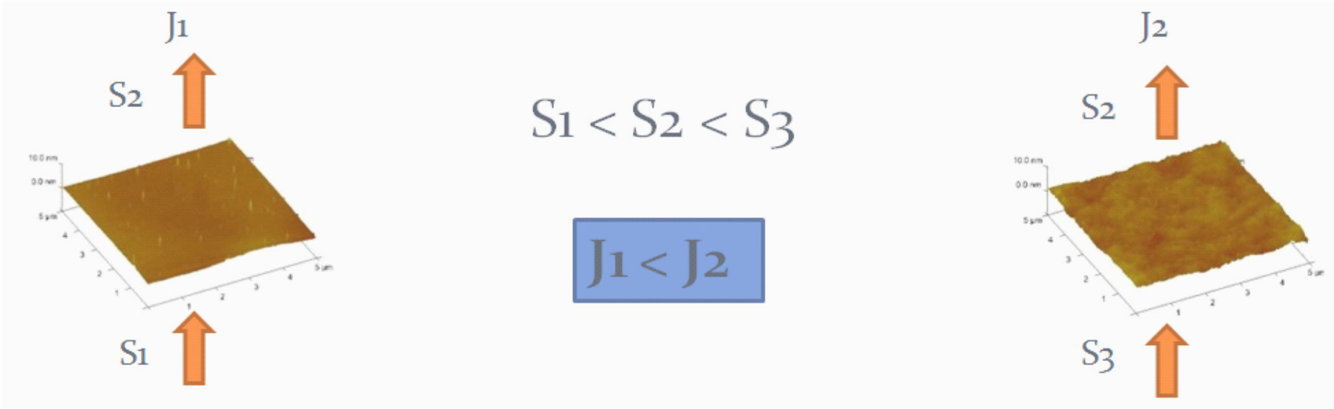


Figure 4.
Growth rate (J) of a smoother crystal grown first at lower supersaturation (S_1, left) will be lower during the subsequent growth at supersaturation S_2 than of a rougher crystal grown first at higher supersaturation (S_3, right).

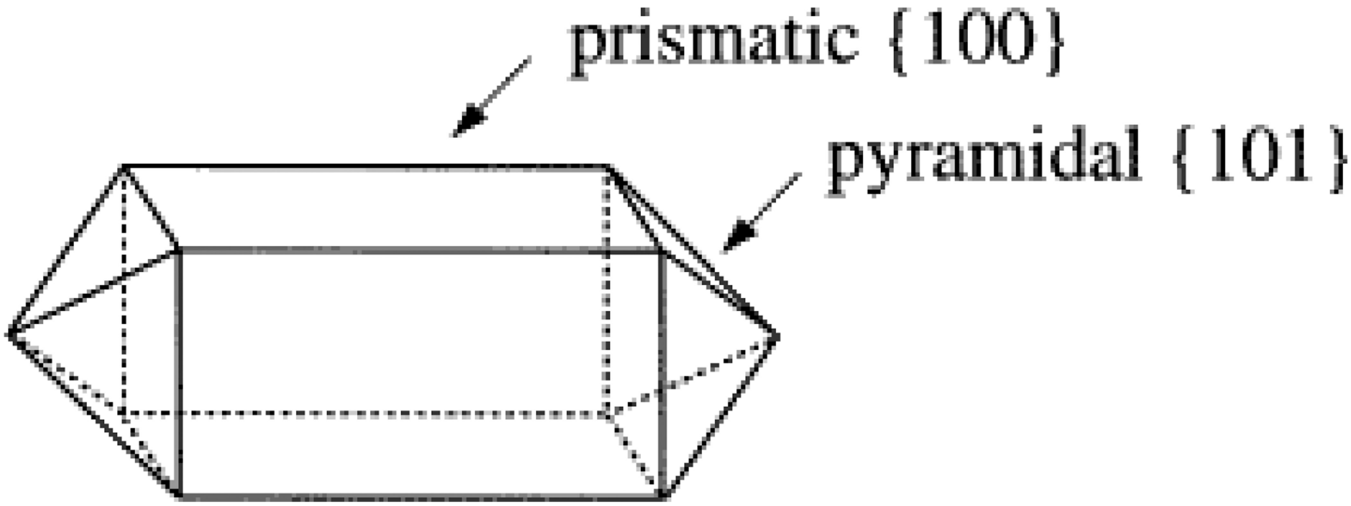


Figure 5.

The pyramidal planes of a hexagonal crystal lattice grow faster than the prismatic ones, diminishing their presence on the surface of the crystal thereby.

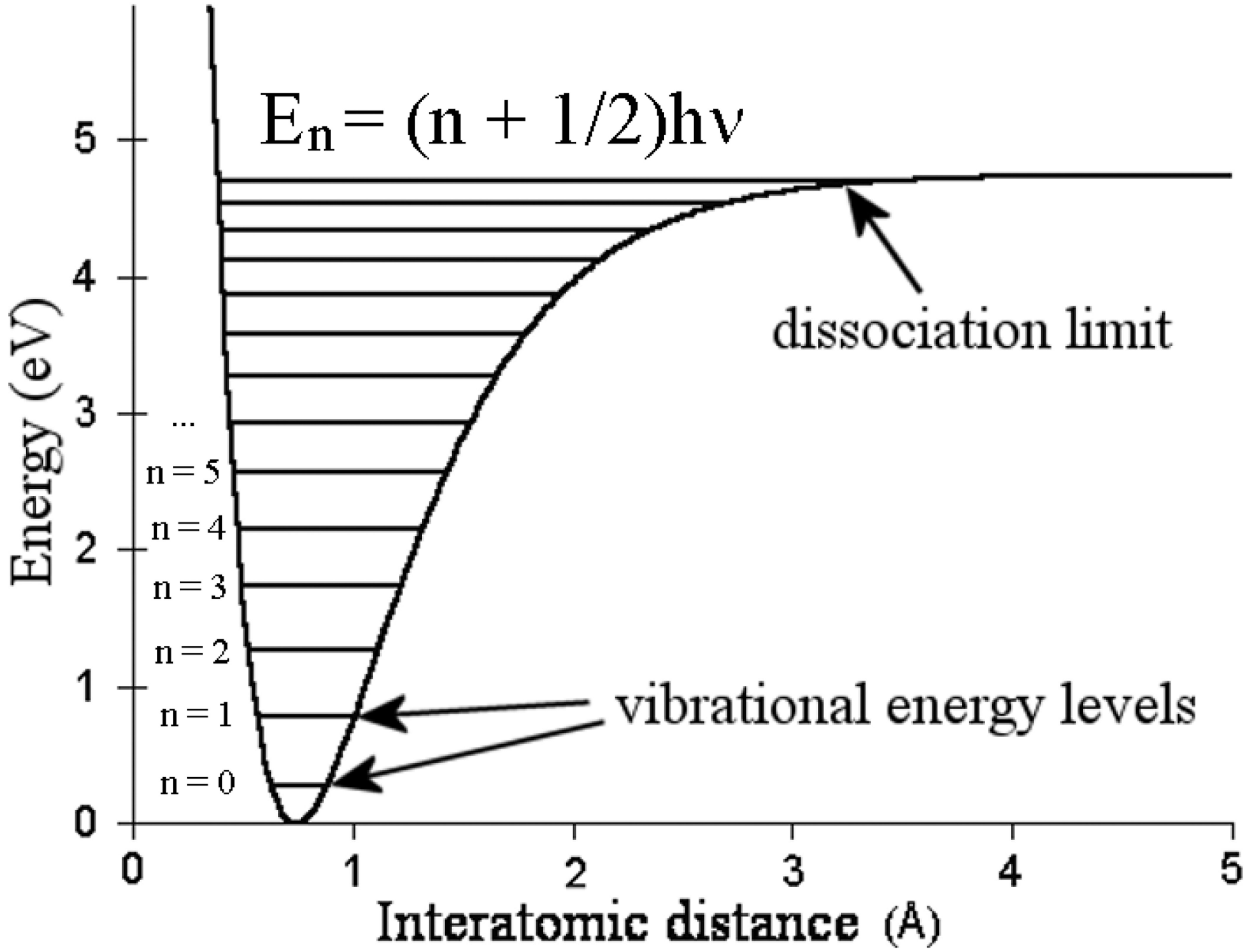


Figure 6.

Vibrational energy levels of an anharmonic oscillator representative of longitudinal oscillations of atoms in a crystal lattice, showing finite vibrations in the ground state existent at absolute zero. The vibrational energy, E_n, is given as a function of the vibrational quantum number, n, the Planck constant, h, and the vibration frequency, ν.

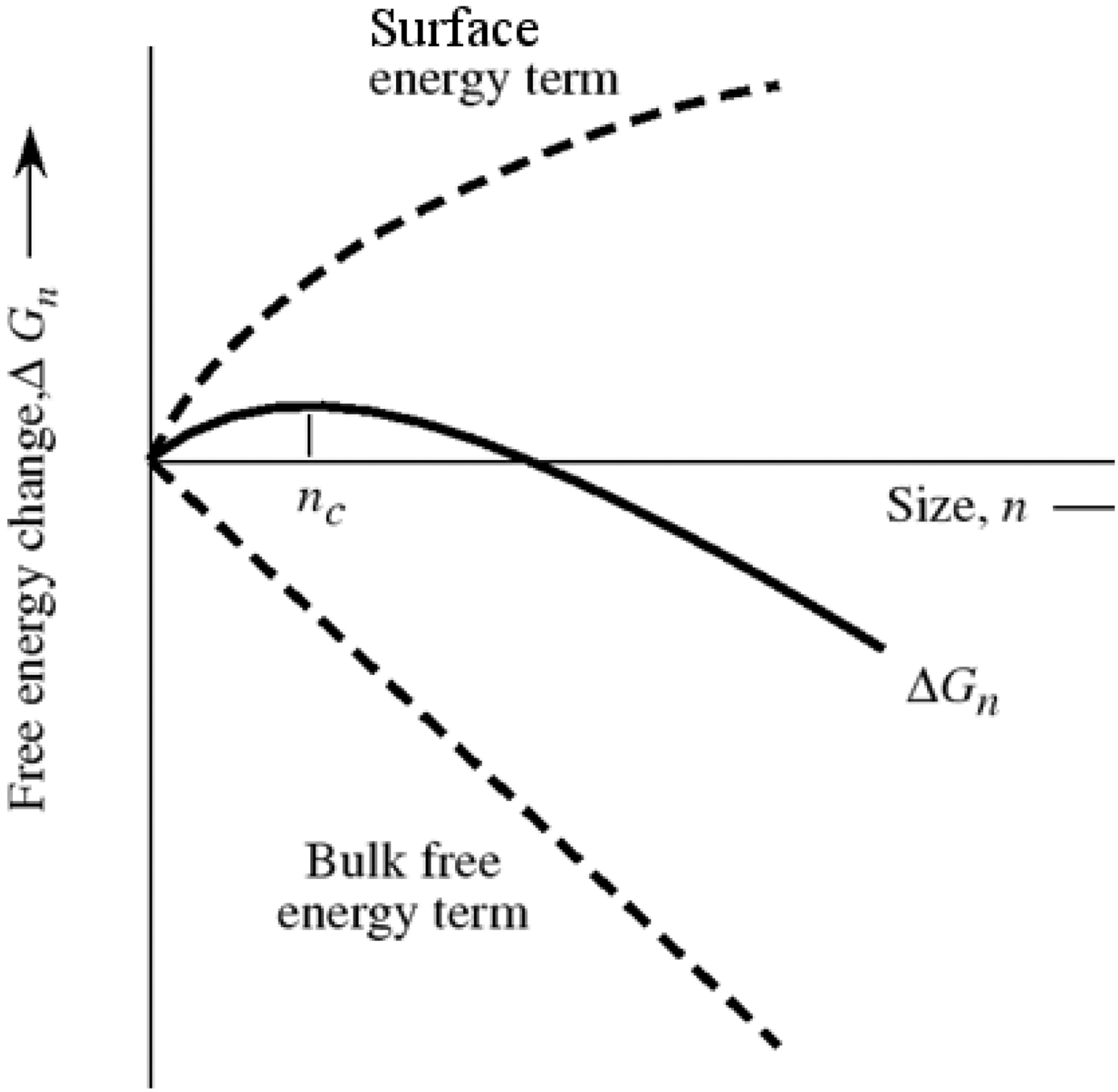


Figure 7.
Free energy change during the nucleation of a new phase, with ΔG_n denoting the net free energy equal to a sum of the bulk free energy that favors crystal formation and the surface free energy that disfavors it, and n_c denoting the critical nucleus size.

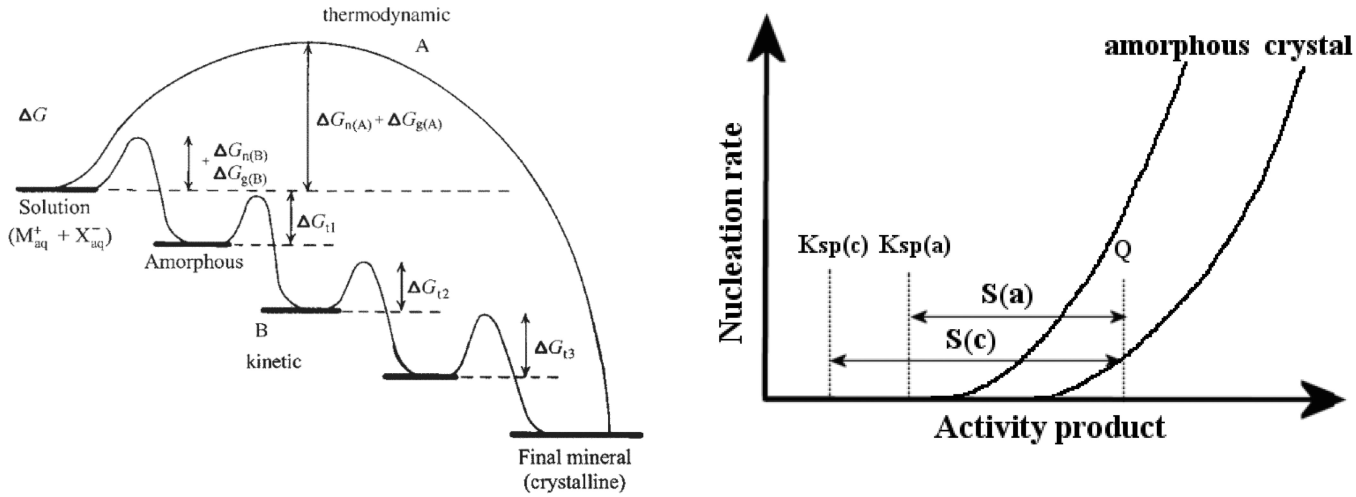


Figure 8.

An inability of the system to traverse multiple energy barriers posed on its way to the final, most energetically favorable state implies its transition through a number of transient stages. As the Ostwald-Lussac rule suggests, the less stable polymorph will pose the lowest energy barrier in front of itself, so that the precipitated ions will adopt it as one of the temporary states on their way to settle into a more stable phase. The image on the left is reprinted with permission from Ref. 37. The diagram on the right demonstrates that even though supersaturation may be higher for a crystalline phase (S(c)) than for the amorphous (S(a)), the nucleation rate of the amorphous phase is higher at any given value of the product of ionic activities (Q), which is a consequence of a lower supersaturation being offset by a reduced interfacial energy.

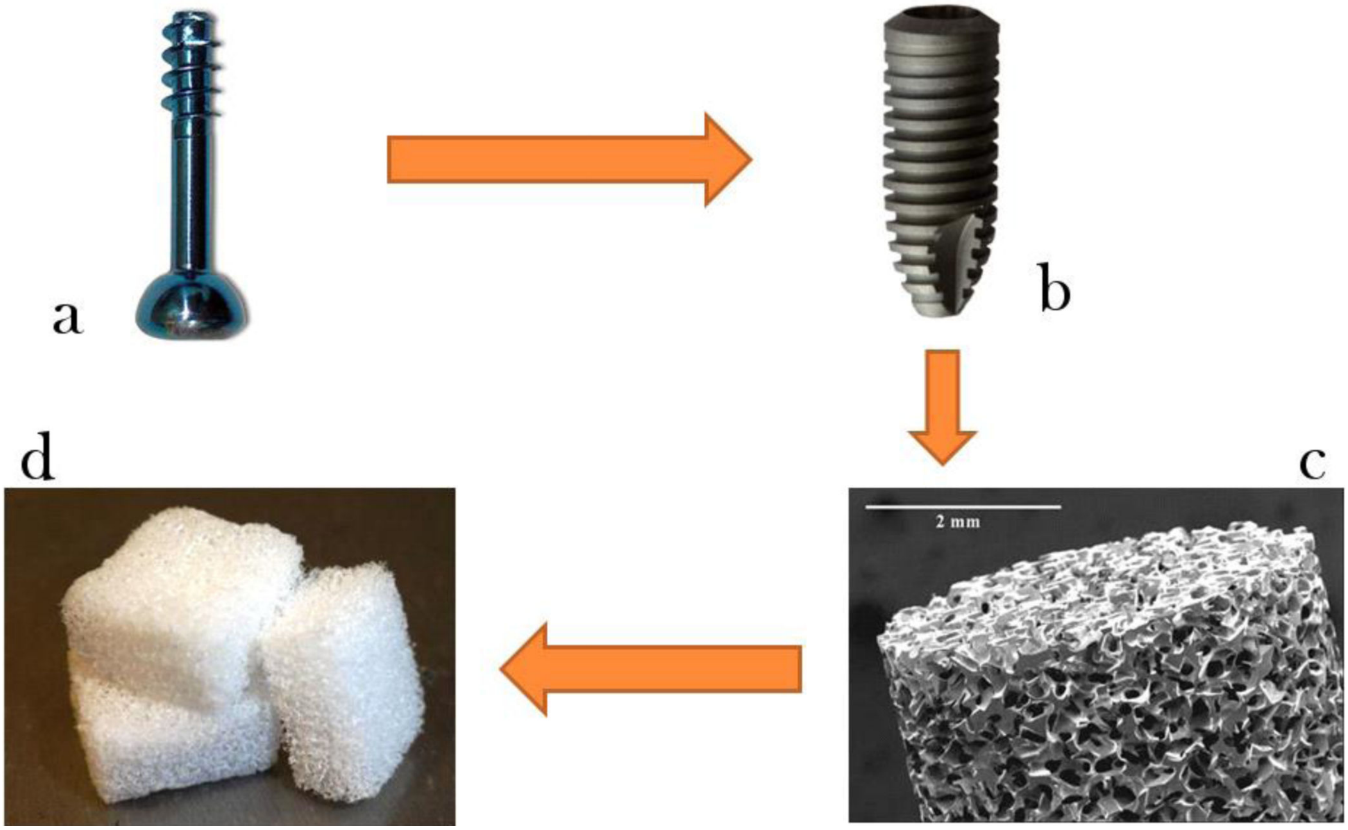


Figure 9.
Polished titanium implants (a) were for a long time considered the best choice for a hard tissue implant because of their superior elastic properties. Then it was discovered that adherence and internal proliferation of cells would require introduction of topographic irregularities (b) and macroporosity (c), respectively. Their non-biodegradability and the tendency to weaken the surrounding bone and cause its resorption have contributed to their substitution with softer, less biomechanically superior materials (d).

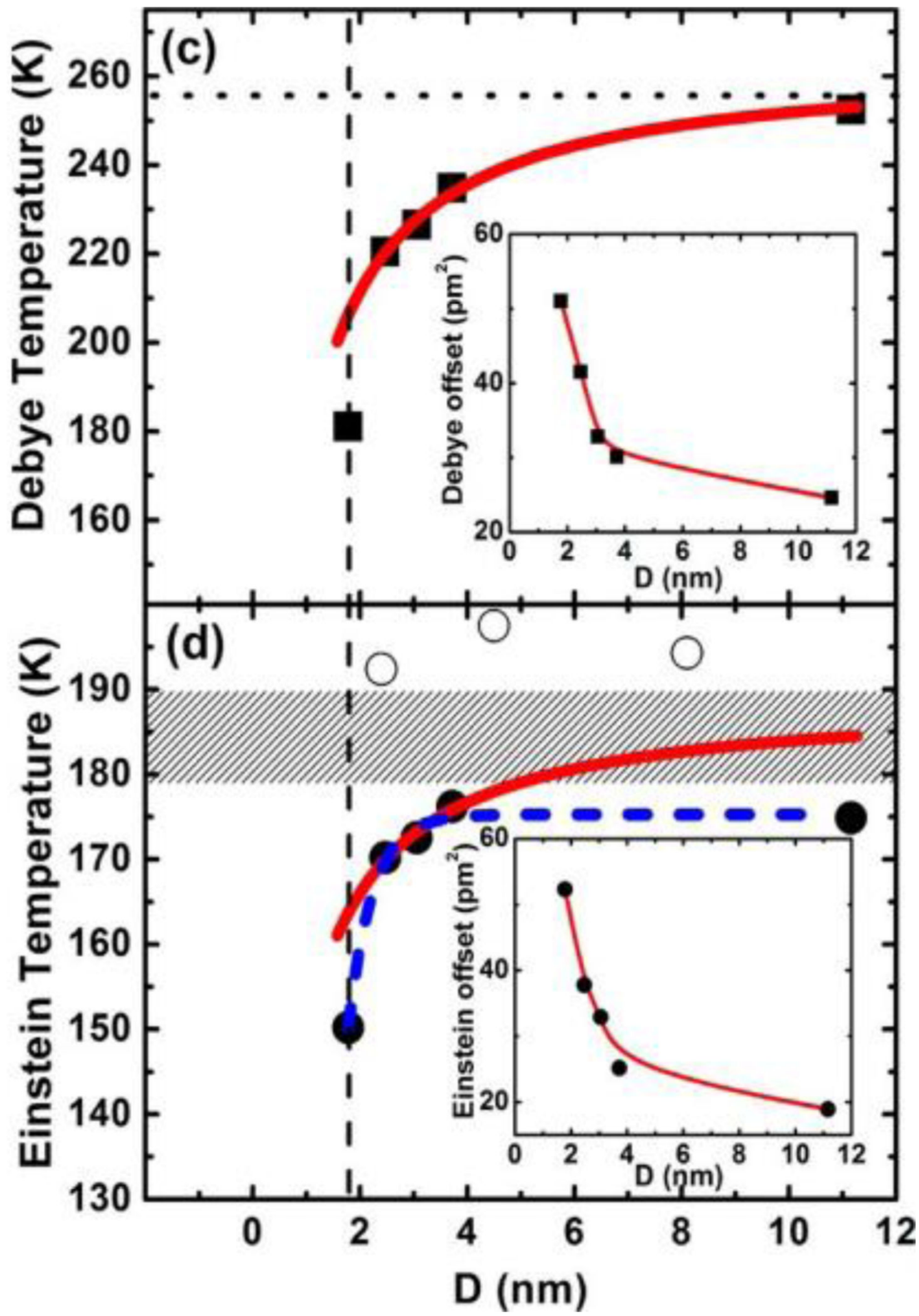


Figure 10.

A decrease in Debye and Einstein temperatures entailing a decrease in Pt particle size below ~ 12 nm. Reprinted with permission from Ref. 46.

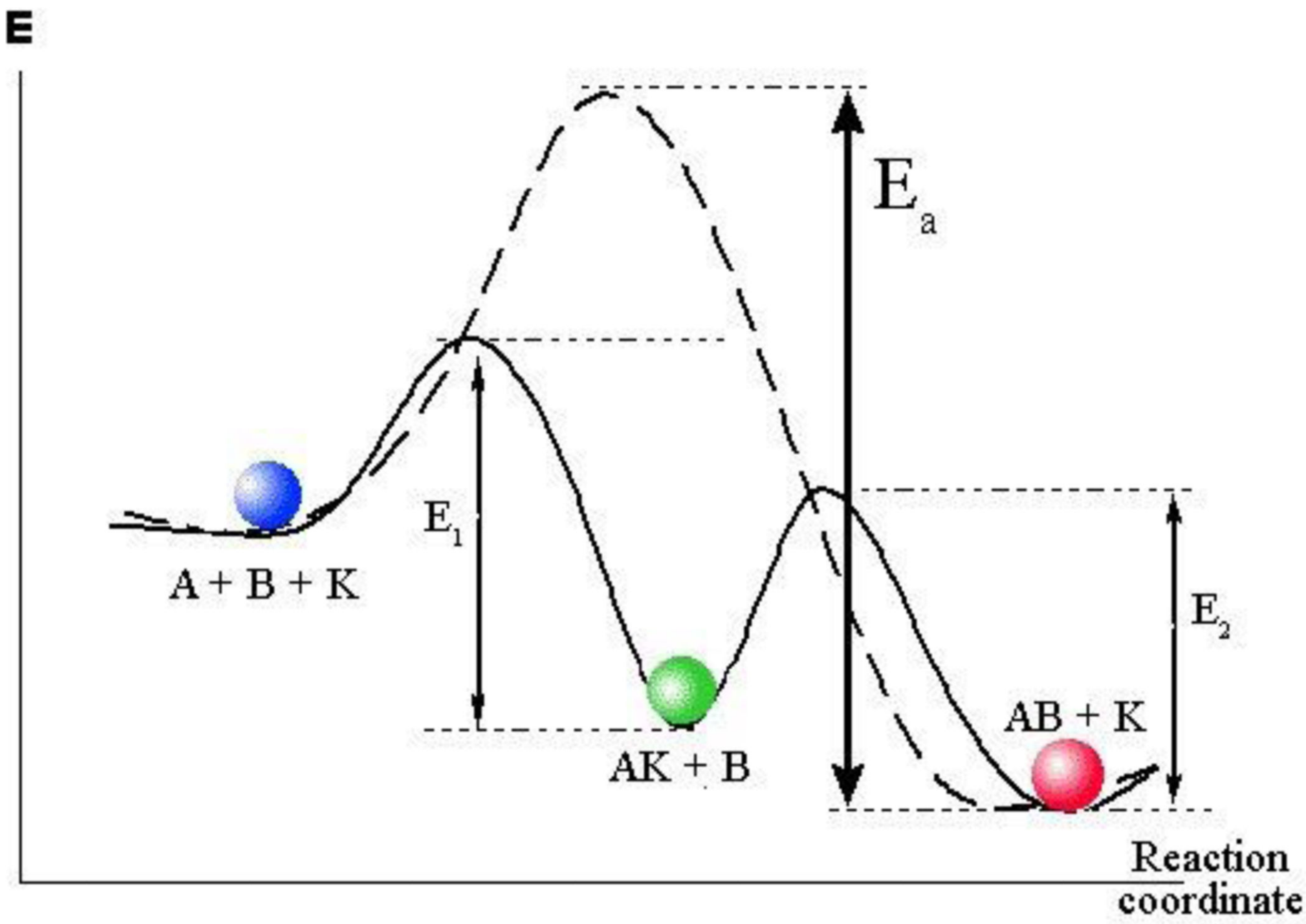
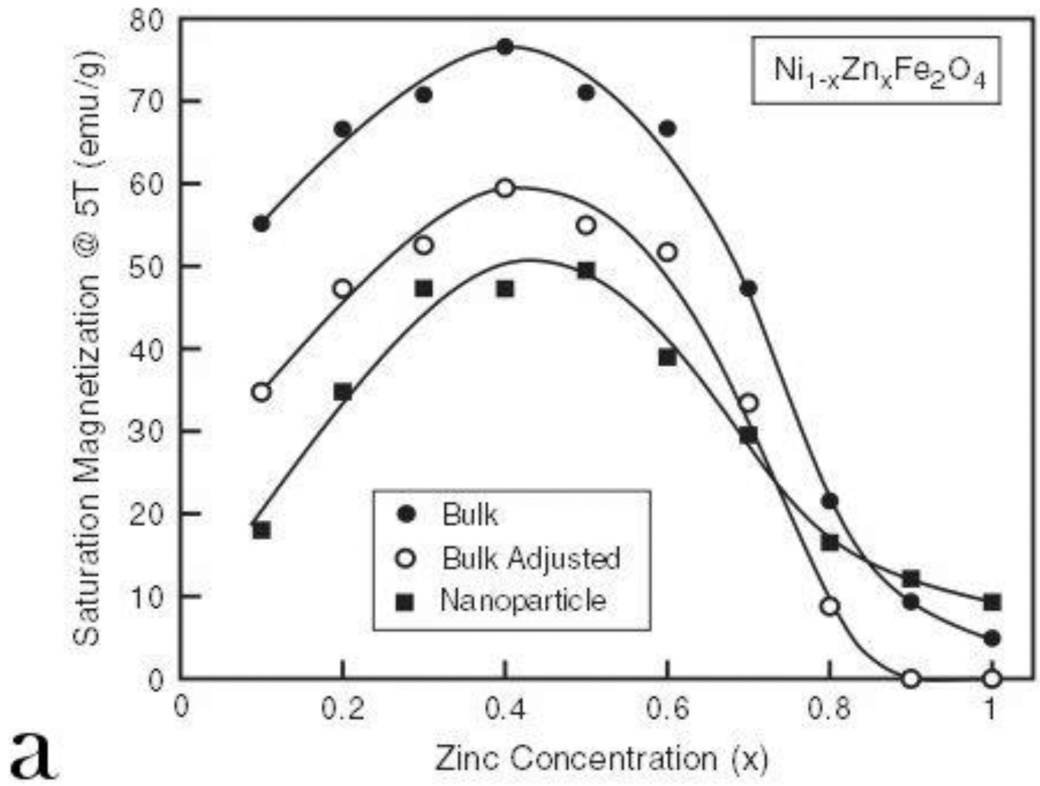


Figure 11.
A kinetic curve for the reaction A + B = AB with and without the catalyst, K, whose role is to break down a single reaction path defined by a rather large activation energy (E_a) to multiple paths, each one of which is associated with lower energy barriers (E_1 and E_2).



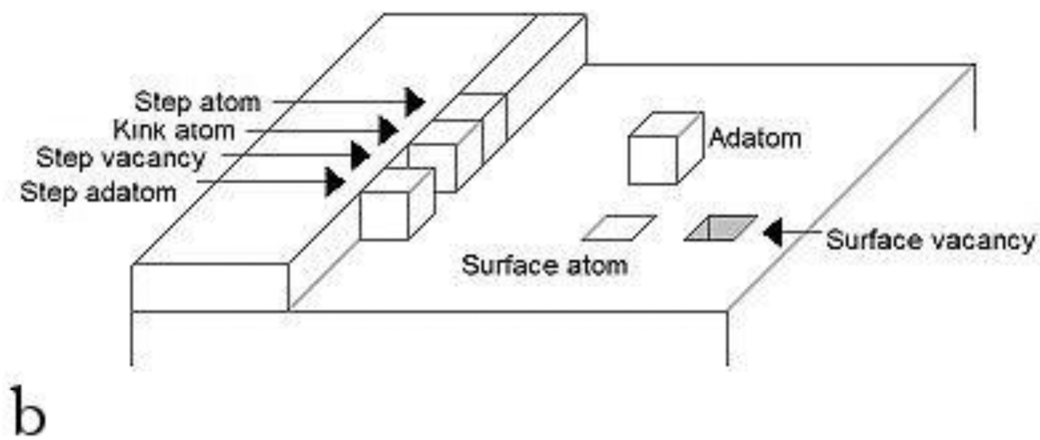


Figure 12.

Saturation magnetization of $Ni_{1-x}Zn_xFe_2O_4$ increases with the initial addition of diamagnetic Zn^{2+} and reaches a maximum at $x \approx 0.4$ (a). Crystal surface defects, such as steps, kinks, terraces, vacancies and adatoms present the primary points of anchorage of adjoining atoms from the solution (b).