Chapter 7
Advanced Sciences Convergence to Analyze Impact of Nanomaterials on Environment, Health and Safety

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Abstract We present Advanced Sciences Convergence (ASC) to develop a risk assessment methodology of nanomaterials towards environmental health and safety from an applications perspective. This enables nanomaterials to be examined more effectively because applications depend on risk assessments by potential users who are likely to display a range of risk thresholds. Results of certain tools, such as TechFARM™, ADAMS™, and NESTS™ are discussed in the context of societal benefits that nanotechnology may offer. Strategic decision-making requires a knowledge base, analytical capability, foresight, risk-assessment, and optimization. The methodology and results presented here will assist strategic policy implications of the use of nanomaterials and their environment, health, and safety (EHS) implications. The basic premise of the methodology is to provide a vision into the future by scientific and cross-validated models that can address the contingent nature of many of these applications, and thereby help us prepare for and so help to mitigate whatever risks or be more ready to act on opportunities that may arise.

Keywords Science convergence • Risk-assessment • Nanomaterials • Foresight

7.1 Introduction

Advanced Sciences Convergence is one of the methods that unify the divergent methods and several overlapping fields in science and technology (S&T) employed for Technology Futures Analysis (TFA) and techniques of futures studies.

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The process of ASC is to understand how advances in different disciplines and focusing on discrete problems and applications can coalesce to solve a seemingly obdurate problem. The synergy arising from the convergence of nanotechnology, biotechnology, information processing and cognitive sciences (NBIC) and other fields offers great potential for transformational and revolutionary opportunities with many applications. Within these interacting systems, or resulting convergent applications, it may be difficult or just not practical or useful to even try to discern the role or precise contribution played by any one element of the convergent system. More importantly, the applications provide new capabilities to understand natural world, human society & scientific research as closely coupled, complex & hierarchal systems.

Recent advances in both sciences and technologies have provided the means to study, understand, control, and articulate and precisely control transitional characteristics between isolated atoms and molecules and bulk materials. Materials exhibiting desired characteristics and devices and systems designed with specific and targeted applications have been fabricated. Notwithstanding realization of such advances, a key issue concerning nanotechnology is how to best protect human health, safety, and the environment as nanoscale materials and products are researched, produced, manufactured, used, and discarded. As the natural sciences have evolved into a wider variety of specialties, with biology for example, including biophysics and synthetic biology, plus many other subspecialties, and new capabilities are emerging in materials with reduced dimensions through the addition of new and powerful linkages.

While the rapidly emerging field of nanotechnology offers significant economic and societal benefits, there are some indications by way of research about the potential and perceived adverse EHS implications. In addition many of these impacts are still more prospective than actual insofar as they are only beginning to be developed and yet in the spirit of preparedness and health and safety, it is both timely and essential that we use techniques such as foresight to anticipate, analyze and understand how convergent systems may affect us and any risks and uncertainties they may carry with them. It is thus critical to evaluate potential detrimental effects of nanoscale materials and devices – both real and perceived – to enable an effective cost-benefit analysis.

Using nexus of technologies and ASC, the systemic properties of these adjoining and intersecting scientific approaches are enabling new insights and new ways of analyzing prospective societal impacts of the products of these same forces such as nano-materials and nano devices, as shown conceptually in Fig. 7.1. Conjoining the nexus of technologies and ASC that enables creation of this system-of-systems approach, we employ the same set of tools to develop a risk assessment methodology of nanomaterials with applications in EHS. This is important because ASC addresses the "nano" challenge from an applications perspective (prospective and currently available) which enables nanomaterials to be examined more effectively because applications are more grounded in real risk judgments by potential users who are likely to display a range of risk thresholds. A successful introduction of nanomaterials in product development is based on exhaustive, evolving, and

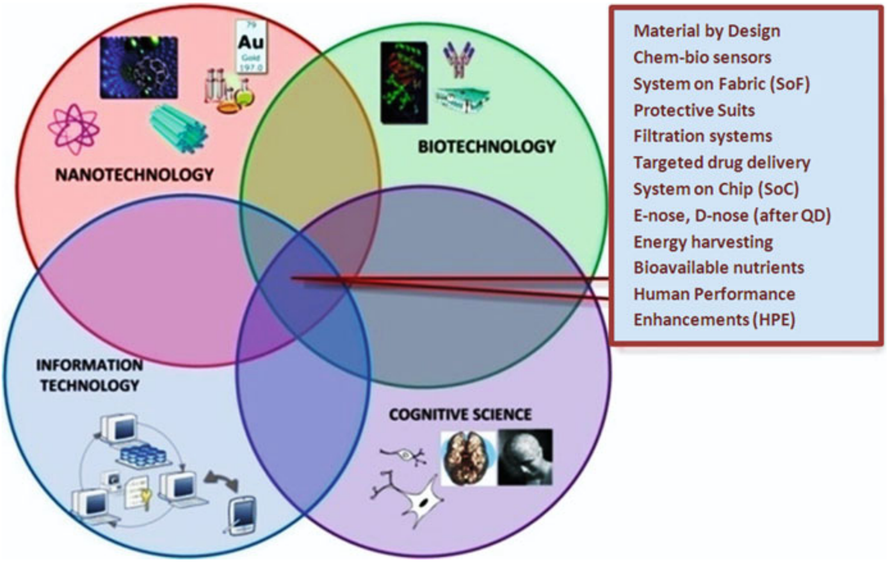

Fig. 7.1 A conceptual framework displaying Convergence of Nanotechnology Biotechnology Cognitive Sciences & Information Technology [1]

innovative approaches of objective risk assessment. The study includes incidental as well as engineered nanomaterials, to ensure an inclusive database for investigation. Study further includes fate and transport and ontological modality of nanomaterials.

The study is intended to be used by strategic decision-makers on policies relating to EHS. Foresight in S&T involves examining the properties and capabilities of derived knowledge and asking three basic kinds of questions:

- *What if*....these capabilities are able to develop-produce effects, viz. x or y; or $x + y = z$;... *then what?*
- *How might these capabilities evolve from here forward,* within a systemic context of developments in related sciences, such as: ecology, neuro-science, systems biology, or nano-scale molecular manipulation and advanced informatics?
- *How wide or narrow and how far out in time should our kaleidoscope of socio-economic and policy perspectives be framed?* -given systemic forces and our (or our clients and stakeholders) need for reasonably confident – but still contingent -anticipatory knowledge of prospective applications that would affect policy or economic actions.

7.2 Exploring ASC as Foresight Tool

Some of the most familiar tools to explore foresight include environmental scanning, scenario planning, technology mapping, road-mapping, expert technical panels, robust factor analysis, strategies development, web virtual conferences, computerized modeling, and dynamic simulation. To explore this realm, a methodology termed "Technology Foresight, Assessment, and Road-Mapping" (TechFARM™) [1, 2] – a multi-dimensional futures-oriented modality that identifies and manages emerging and/or disruptive science and technology trends is articulated in context of interaction of nanomaterials with human, toxicity, and fate and transport of nanomaterials in environment.

ASC essentially originated in the 1980s with the developments of advanced-networked computation methodology that was enabled largely by personal computers and nanotechnology "discovery" and have accelerated since 2000 with advances in systems and synthetic biology made possible by speed and capacity growth in computation. The examples below illustrate how these three intersecting domains are revolutionizing science through the new capabilities they can deliver individually and collectively.

Example 1: Trends in Nanotechnology – Smart materials with integration of functions and structure in membranes;, self-powered and healing fabrics and fibers; biomimetic materials; contamination specific water filtration and purification [3] – biocides, pathogens, and pharmaceutical remediation/decontamination; sensor networks with tracking capacities; NEMS – nano-electro-mechanical systems (NEMS);wearable personalized flexible sensors with data/communications capabilities; energy and power harvesting capabilities; battery power management; smart dust capability for wide area surveillance; functional, programmable, and targeted structures for controlled drug delivery, performance prostheses; climate responsive building materials.

Example 2: Trends in Biotechnology – Control/improvements in organisms; sensing at the micro/nano level, integration with wireless/RFID/nano-photonics; tissue engineering, artificial organs, implants and prostheses; targeted drug delivery; *in-vitro* diagnostics capabilities, regenerative medicine; medical diagnosis and forensics; personalized medicine using large data sets of patient information, disease statistics, gene sequences and genotypes; genetically modified insects to counter pathogen carriers; *in-silico* testing&comprehensive modeling for drug characteristics, side effects and receptor simulation; lab on chip (LOC) and system on fibers (SoF).

Example 3: Trends in Information Technology – Progress toward ubiquitous access and embededness; Open source collaborative tools and deeper peer- to peer functionality; pervasive social networks; migration towards functional convergence; claytronics for distributed fabrication; object based nodes and networks for smart and ubiquitous connectivity; pervasive sensor networks with dynamic simulation and modeling; gaming for personal and organizational decisions, risk abatement and learning; emerging horizons for faster, exponentially more powerful encryption, quantum information; sustained information growth for surveillance, sensor networks, and tracking capacities.

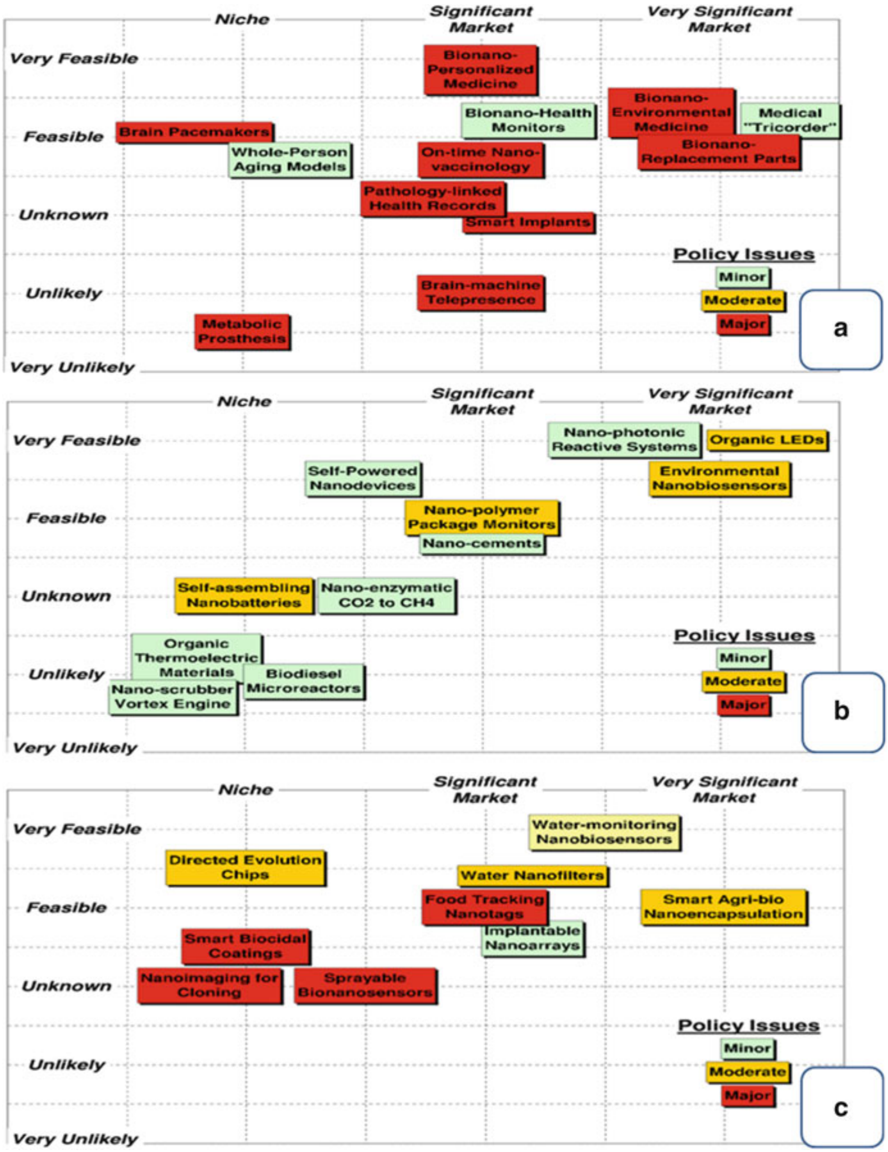

Fig. 7.2 Domain intersection matrix approach for (**a**) health and life sciences, (**b**) energy and environment, (**c**) water, food, and bio-fuels

To examine some of these intersecting capabilities and trends further in terms of domains of application, technologies that could or would be created to identify potentially transformative applications, we developed a series of matrix analytical tables to portray this process and its initial results. Figure 7.2a–c demonstrate domains and technologies can evolve using such intersections.

Adapted from the Rand Corporation, these matrix tables rely upon experts to evaluate prospective applications on the basis of three attributes – market appeal and commercial potential; technical readiness and feasibility; and the perceived degree of complexity-barriers in terms of how the applications may be publically received, impact or stir up (or not) strong public policy concerns, issues and debates. This complexity can be tied into foresight of any desired technology or innovation outcome, in this case, the application being the EHS aspects of nanomaterials.

With the addition of cognitive sciences, the convergence is then critical towards understanding the human mind that imagines-designs-creates-evaluates-decides, and eventually approves or executes actions. Emergence of incorporation of cognitive is demonstrated in autonomous and self-learning designs and we await full implementation of these new capabilities– at least for a few more years until the arrival of – what is termed as the Singularity- that would likely transform this aspect of convergence enormously.

7.2.1 Challenges and Complexities

In a foresight context, as these new capabilities begin to be more rigorously investigated, described, and examined, it undoubtedly requires a comprehensive paradigm and new integrated modalities capable of advanced simulations for the future analysis. An initial need will be for a more iconoclastic and futuristic scanning coupled with – what if – questions, termedhere as “provocative scanning”.

A second applicable technique is the Protean or Proteus project approach – a series of intelligence insights, lenses or perspectives that have emerged from many focus groups of US intelligence professionals and military strategists. The Proteus approach offers an elaborative description of the uncertainties and the resulting implications and environments that are being shaped by the emerging new challenges and realities. Proteus is a set of foresight tools and insights premised upon asymmetries of action, intent and impacts, aimed at exploring unforeseen implications and consequences of actions undertaken under conditions of threat, surprise, disruption and disorder.

This dynamic and algorithmic set of tools relies upon real-time human group simulation wherein complexity is built into the fabric and structure through ten key insights which have been codified into the Proteus Critical Thinking Game [4, 5] as ‘forces’ that are available to participants. It is a foresight game in which there are no clear winners – just choices, actions and consequences as revealed by the game record and evident and/or steal the strategies that can be analyzed in after-action reviews for insights into the complexity of the serious behavior and game play exhibited.

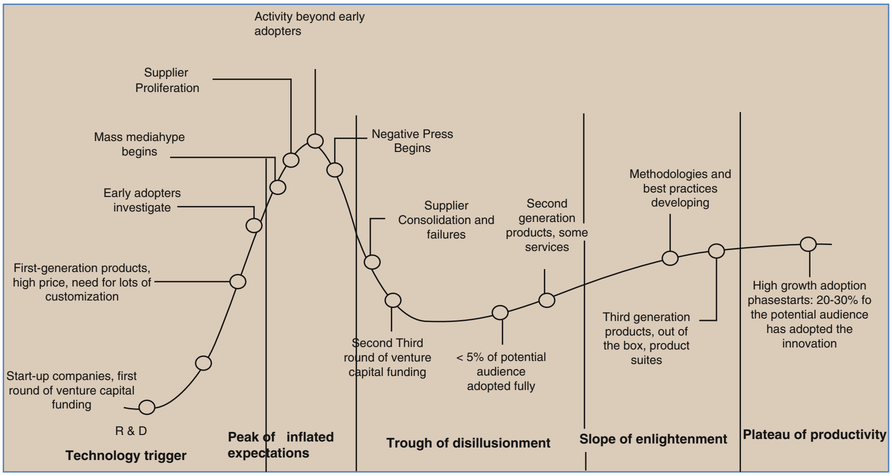

Fig. 7.3 S-curve of macro-economic context

7.2.2 Characterizing Innovations Involving Convergence

There are many ways to evaluate how well positioned a particular technology or application may be for public acceptance and/or commercial success i.e. to be regarded as an innovation. And while most innovations can be described as incremental, many, especially those derived from advanced S&T sources like our convergence methodology [1], could be characterized as disruptive, radical or potentially transformative. By distinguishing what type of market situation an application-innovation is aimed at changing, we developed “Technology Assessment Matrices (TAM)” for specific sectors. Another set of characterization criteria can be employed to focus on Technology Gaps and by using TAM 9 [6, 7], at least a rudimentary comparative insight into which ones might be the most accessible and practical from a strategic choice perspective, or where further analyses might be focused. Finally – it is also important not to forget that all technologies are not only positioned in time but also against other technologies in cycles of S-curve development which in turn can be subjected to hype, maturity and macro-economic context, as demonstrated in Fig. 7.3 below.

7.3 Challenge – Nanomaterials and EHS Related Issues

We use the foresight methodology described above in the context of nanomaterials and its possible impact on environment, health and safety, after a brief synopsis of the issue.

Reduced dimensional aspect attributes that provide novel characteristics are also believed to be responsible for bioadverse response pathways for toxicity of nanomaterials. Consequently, nanoparticle toxicity is studied in context of its ability to induce tissue damage through the generation of oxygen radicals, electron–hole pairs, and oxidant stress by abiotic and cellular responses resulting in pro-inflammatory, mitochondrial injury and pro-apoptotic cellular effects in the lung, cardiovascular system and brain [4]. It is further believed that nanoparticles absorb cellular proteins which could induce protein folding and thiol cross-linking; leading to neuro-toxicity and reduced enzymatic activity.

Nanoparticles which are cationic in nature are also believed to induce toxicity via acidifying endosomes that lead to cellular toxicity and apoptosis in epithelial lung through endosomal rupture through proton sponge mechanism (PSM), mitochondrial targeting, and cytosolic deposition. Nanomaterials composed of redox-active elements are particularly reactive and can possibly provoke potentially damaging chemical transformations. Furthermore, even chemically benign nanoparticles may become activated by light absorption. It is thus essential to investigate the long-term consequences of NPs upon crossing blood–brain-barrier (BBB) and its distribution in cortex and hippocampus over time to ensure their safety using a set of tools termed as Nanopathology, such as x-ray fluorescence microscopy (XFM) for distribution, magnetic resonance imaging (MRI) to measure metal concentrations in cerebrospinal fluid, etc. One approach to determining the safe application of nanomaterials in biology is to obtain a deep mechanistic understanding of the interactions between nanomaterials and living systems (bio-nano-interactions).

7.4 Recommendation, Conclusions, and Path Forward

As described earlier that S&T Foresight involves systematic attempts to look into the longer-term future of S&T and their potential impacts on society, with a view to identifying the emerging change factors, and the source areas of scientific research and technological development likely to influence change and yield the greatest economic, environmental and social benefits during the next 10–25 years. The approach we are taking relies upon consulting a wide range of expertise, with the expectation that through our collective experience, imaginative abilities and interactive knowledge of technological development pathways, we can begin to construct a coherent view of some of the major developments that can be anticipated within a 10–25 time horizon. Foresight is therefore research that can inform planning, policy and strategic choice amidst uncertainty. By employing the ASC approach, inconjunction with TAM and Protean approaches, the following recommendations are provided.

1. It is critical to evaluate the exposure pathways of engineered, incidental, and nanomaterials produced in nature.

2. Study of fate and transport of nanomaterials via a matrix of parameters such as exposure routes, chemical composition, distribution, metabolism, and agglomeration and excretion rate provide a comprehensive overview of interaction pathways.
3. An ontological modality to identify its relationship to other items in the lexicon; viz. to enable information retrieval from various sources, databases, and via expert elicitation.
4. Studying other contributing factors that range from biodegradation and bioaccumulation, thermodynamic properties, interfaces, and free energy of nanoparticles as a function of particle size, composition, and phase and crystallinity influence particle dissolution in a biological environment. The accumulation, dispersion, and functional surface groups play an important role in cytotoxicity and in evaluating pathways of cellular uptake, subcellular localization, and targeting of subcellular organelles.

A fundamental understanding of a nanomaterial-surrounding medium is vital to sustaining technological advances of nanoscale materials as catalyst for new scientific and technological avenues. Use of ASC and foresight methods described will assist researchers, policy-makers, and end-users in responsible use, discard, and recycle of nanomaterials based products.

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