# Exploring NEMS as Emerging Technology

ETM 571

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# Contents

# 1.0 Background

## 1.1 What are NEMS?

**NEMS**: NEMS is an acronym for Nanoelectromechanical systems. NEMS have the potential to extend device miniaturization to the molecular level. NEMS are synthetic devices with functionality at the nanometer on a length scale (between 1 and 100 nm). The term NEMS is often applied to electromechanical systems operating at the meso-length scale (between nano and micro).

NEMS have structural elements at or below 100 nm, microelectromechancial systems (MEMS), have structural elements on the micrometer length scale. Evolving from MEMS, NEMS have intrinsically smaller mass to surface area to volume ratios which make them candidates for applications like high frequency resonators and ultrasensitive sensors.

Engineers and physicists are pursuing device miniaturization utilizing NEMS technology by assembling mechanical devices on the nanometer scale. It could be said that the miniaturization of electronic devices has transformed the technology of today, and the miniaturization of mechanical devices will transform the technology of the future. NEMS are built with nanosensors, nanoactuators, nanoresonators, nanoaccelerometers, and integrated peizoresistive detection devices, etc. Nanoelectromechanical systems (NEMS) may enable applications including: atomic mass and force sensing, displays, portable power generation, energy harvesting, imaging, efficient energy conversion systems and quantum computation. Potential bio-applications could be ultrasensitive sensors that can detect subtle genetic alterations responsible for a disease, drug delivery, artificial muscles, superior prosthetics, or tiny 'robots' for surgery or diagnostics.

NEMS can be designed for a singular and specific functionality, or collections of NEMS can be designed for multifunctionality and greater utility. Specialized NEMS increase functionality when assembled with other specialized NEMS. Collectives of NEMS may potentially find applications in: targeting and payload delivery, data gathering with social learning and memory pooling, computational sharing, and aggregation.

Collectives of NEMS may embody functionalities to designate the collective as a "Nanorobot." This could be thought of as a system integrating nanoelectronic components in a NEMS device which may include the following components: a nano-scale sensor, a nano-scale actuator, a nano-scale integrated circuit with nano-scale computing memory, a nano-scale communications device comprised of nanofilaments, and  a nano-scale power supply.The NEMS device may use computational functionality to analyze sensor data and adjust position The NEMS device may contains functional components to attach and detach from other NEMS devices. The NEMS device uses communications functionality to send and receive signals. Future NEMS devices are imagined with the ability to sense or input their environment, process that sensory information and then output a programmed response. NEMS would be able to send and receive information for a dynamic computation of a response.

**1.2 The details of the science & technology involved**

Nanotechnology has evolved in what could be reduced to four phases. The first phase was focused on developments involving chemical composition (ie new nanomaterials). The second phase involved the production of simple nanostructures like tubes and filaments by building structures through bottom up nanomanufacturing with molecular scaled units. The third phase produced nanodevices with specific functionalities. The fourth phase produced self-assembling nano-devices using novel chemical assembly techniques.

The current state of technology builds on the previous four phases and introduces the potential for intelligent collectives of NEMS. Intelligent NEMS are self actuated. Self-guided or self-computing processes may be possible at the nano- and micron-level with nanoelectronics and nanomechatronics. Future NEMS devices are imagined with the ability to sense or input their environment, process that sensory information and then output a programmed response. NEMS would be able to send and receive information for a dynamic computation of a response.

Understanding the fundamentals of biological nano-machines may be the first step to realize man made nano-machines.  At the nano- scale, there is a confluence of energy, and the interactions between thermal and deterministic forces support the opportunity for diverse behavior in molecular machines. Billions of years of evolution have found that at this scale, energies converge, and there is the opportunity for complex physical phenomena and processes that can be utilized for both living and non-living developments. Also, the nano-machines highlighted in the article “The Biological Frontier of Physics” have proven that at this scale, highly efficient and reliable machines have evolved [4].

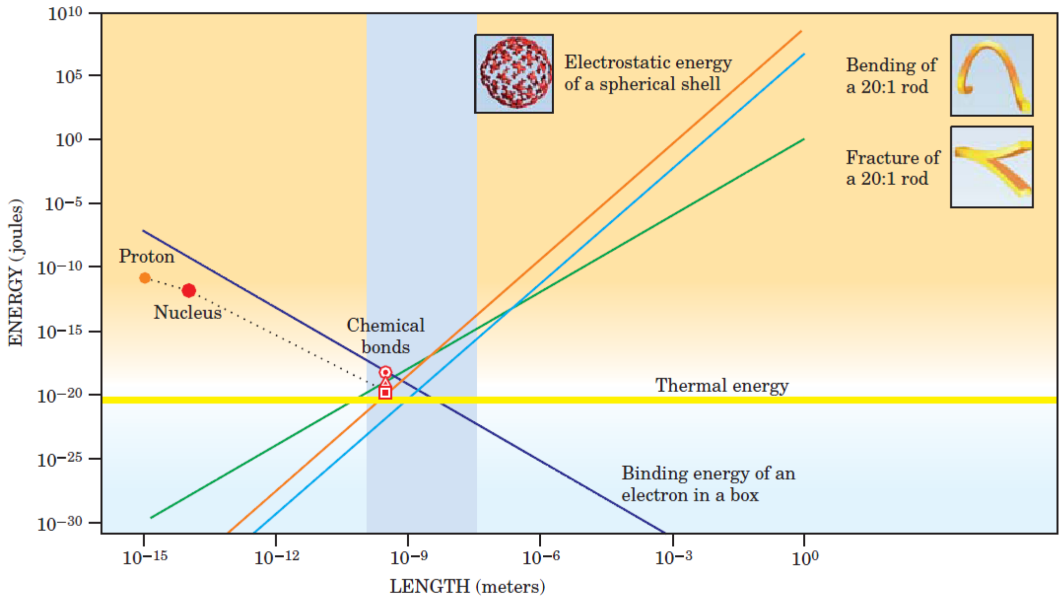



**Figure 2. The confluence of energy scales** is illustrated in this graph, which shows how thermal, chemical, mechanical, and electrostatic energies associated with an object scale with size. As the characteristic object size approaches that at which molecular machines operate (shaded), all the energies converge. The horizontal line shows the thermal energy scale $kT$ which, of course, does not depend on an object's size. We estimate binding energy (purple) by considering an electron in a box; for comparison, the graph shows measured binding energies for hydrogen bonds (square), phosphate groups in ATP (triangle), and covalent bonds (circle), along with characteristic energies for nuclear and subatomic particles. In estimating the bending energy (blue), we took an elastic rod with an aspect ratio of 20:1 bent into a semicircular arc, and to compute the fracture energy (green) we estimated the energy in chemical bonds in a longitudinal cross section of the rod. The electrostatic energy (orange) was obtained for a spherical protein with singly charged amino acids of specified size distributed on the surface.

**Phillips R., Quake S.R. The biological frontier of physics (2006) *Physics Today*, 59 (5), pp. 38-43**

The simple scaling down of existing devices is maybe the most natural if not the most obvious way to visualize nano-machines. Feynman [21] discusses many reasons why we cannot simply take our conventional machines and scale the components down to the nanoscale to make a nano-machine. The predominating reason is that materials at this level are governed by the laws of quantum physics, and classic theories of lubrication, friction, resistance, electricity and magnetism do not hold up at this small scale. There is also an issue of rapid heat loss at the nano level, and Van der Waals forces at the atomic level lead to particles agglomerating or glueing themselves together, so nano components would seize together.  Additionally, Feynman studied quantum electrodynamics, and described how atoms produce radiation. This might be a serious consideration when designing at the atomic scale, or it might not.

In general, the micro-nano domain is subject to quantum mechanical rules of operation of objects not typical at the macro-scale. Key natural forces such as heat, electromagnetic forces and atomic and molecular forces become prominent. Atoms move at this level like syrup. The spinning motions of atoms, particularly as they are excited, can create a distinctive effect. Friction is also a prominent force that limits the functionality of objects at the nano-scale. The intermolecular forces between material are no longer insignificant, intermolecular forces can be ignored at the macroscale, but are significant at the nanoscale.

However, for all the new problems related to designing in the realm of quantum physics, it is the quantum phyics domain which enables the possibility of unique and advantageous properties at the nano-level. The distinct quantum mechanical attributes at the nano-scale are used to design high-performance properties. Molecular forces can be used to reduce the energy needed to manipulate forces at this level. It is possible to use the attractive and repulsive molecular forces to propel nanomechanics. A main focus is creating systematic mechanisms to oscillate between attractive and repulsive forces to produce specific functional objectives.

NEMS can either be produced bottom-up (chemical self-assembly methods, CVD methods), top-down (etched semiconductor layers, scanning probe tools, or nanolithography) or via combined methods where molecules are integrated into a top-down framework. Carbon in the form of graphene or carbon nanotubes has been a popular material used in current NEMS, because graphene has been shown to function in a NEMS device at the nanoscale. Traditional materials used in MEMS have not been able to transition to the nanoscale.

Developments in nanolithography or nanomanufacturing will push the performance of NEMS, and this would lead to smaller, faster and more accurate processors, sensors, switches, accelerometers, etc., which could all become the components in a future "nano-machine." But, we should not necessarily think of these components as being mechanically linked and confined in what we would conventionally call a machine. We should think of these future NEMS based components more as a system having the ability to interact and to develop mechanisms which may function similarly to the mechanisms functioning in a human cell, which can create and deconstruct cellular components, send and receive messages, and process energy.

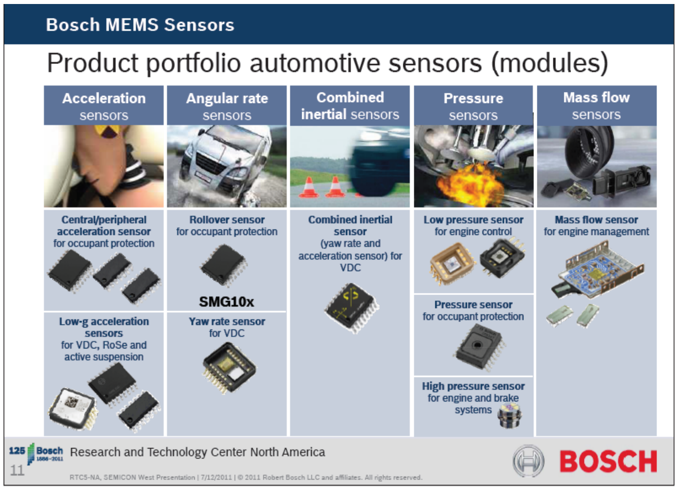
## 2.0 What is the incumbent technology

### 2.1 MEMS

MEMS: microelectromechancial systems (MEMS), have structural elements on the micrometer length scale. These are analogous to the NEMS previously discussed, but their properties will be unique to the physical realm of the micron-level where classical and quantum mechanics converge.

### 2.2 MEMS Applications

A few MEMS products that have been commercialized include: Inkjets, gyroscopic airbag and "smartdrive" sensors, chemical and force sensors for specific applications, accelerometers and oscillators. MEMS research is also accelerating in industry and at national labs and universities. Bosch leads the field for automotive sensors, and HP leads the field for inkjet sensors.




## 3.0 The breakthrough aspect of NEMS

**The breakthrough is that NEMS will enable ultimate low-power devices.** Self-powered, integrated systems for extremely low-power devices for applications in commercial, defense, space, harsh-environment, and medical settings.

NEMS will enable social intelligence in sensors, because the improved communications capability between nano-sensors allows functionality beyond nearest neighbor behavior control.

Imec states that NEMS will enable high-definition holographic displays. The 3D integration of sensors and actuators will add extra functionality to interact and react with our environment. And ultra-low power ultra-high speed versatile radios will fulfill the ever increasing mobility and connectivity expectations of users.

Integration of nano-electro-mechanical switches (NEMS) with CMOS technology has been proposed to exploit both near zero-leakage characteristics of NEMS devices along with high ON current of CMOS transistors. 60-80% lower switching power and almost zero leakage power consumption with minor delay penalty. can achieve almost 8X lower standby leakage power consumption with only minor noise margin and latency cost. Finally, application of NEMS devices as sleep transistors results in up to three orders of magnitude lower OFF current with negligible performance degradation as compared to CMOS sleep switches.

## 4.0 Potential NEMS Applications and Benefits

Nano-electromechanical systems (NEMS), devices with characteristic dimensions in the nanometer range, represent an emerging technology that harnesses these reduced sizes to provide sensing, actuation, computing, and signal-processing functionalities that are not attainable with currently available components. Micro- to nanosize scaling of devices enables development of reconfigurable radio-frequency front ends, miniaturized and sensitive chemical and biological sensors, and low-power computers.

Can be used in buildings and bridges to monitor cracks, stresses and the environment. Because the NEMS have a system functionality, the sensors could monitor conditions and send signals to a monitoring station, and receive signals to send to a LED or other indicator to reveal where a problem is.

NEMS gyroscopes would be more precise for measuring when a vehicle is out of balance, and faster at sending signals to initiate a mechanical correction.

Gaming and mobile devices could be enhanced by NEMS. NEMS could make prosthetics more functional. As sensors, NEMS could detect the mass of a single atom for precision chemical analysis, or could detect trace indicators of disease before a traditional diagnoses would even be performed. An inchworm device could be realized to sense and kill cancer cells in the brain, or otherwise surgically remove things that are too fine or intertwined for a surgeon. These types of devices could also work to repair other fine scale body parts like nerves and veins.

NEMS will also help research by providing a means to make measurements in areas that were previously unmeasurable, and will offer more precise measurements for data analysis and modeling.

### 4.1 Specific examples of NEMS reseach

#### 4.1.1 Nanoresonator

Nanoresonators effectively transfer the external electrical signal into mechanical motion and vice versa. These efforts focus on scaling piezoelectric aluminum nitride (AlN) films from the micro- to the nanoscale realm for fabrication of efficient NEMS resonators and switches that can be interfaced directly with conventional electronics and, therefore, integrated on large scales.

The performance of a NEMS AlN resonators has been demonstrated that vibrates at record-high frequencies approaching 10GHz with quality factors (Q) in excess of 500. Q is an inverse measurement of the energy dissipation in the NEMS device: the higher the Q value, the lower the power consumption. For comparison, at 10GHz, on-chip resonators made with standard components have Q values around 10. The benefit of this application is that AlN piezoelectric nanomechanical resonators exhibit much higher Q values and occupy a fraction of the space taken by conventional capacitors and inductors.

Using 100nm-thick nanopiezoelectric films to develop NEMS actuators for switching applications, we also confirmed that bimorph nanopiezo actuators have the same piezoelectric properties as their microscale counterparts.These actuators define a realistic pathway toward demonstrating nanomechanical computing elements that significantly reduce power consumption in both the dynamic and standby states with respect to state-of-the-art CMOS devices.

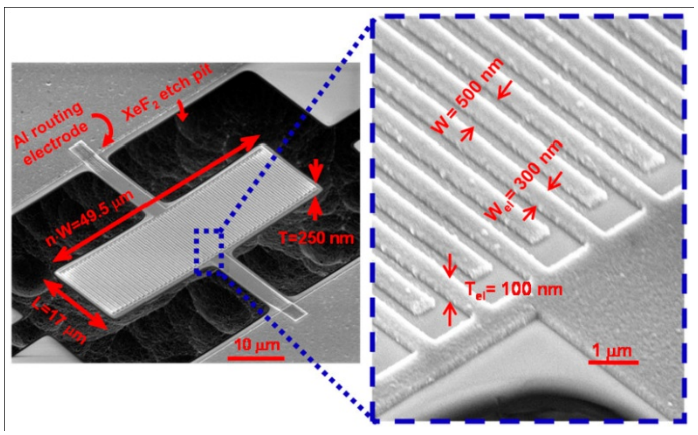



***Figure 1.*** *Scanning-electron micrograph (SEM) of a 250nm-thick aluminum nitride (AlN) nano-electromechanical (NEMS) resonator with 300nm-wide Al electrodes, operating in the superhigh-frequency range. L, W, T: Length, width, thickness. n: Denotes repeating pattern. $W_{el}$, $T_{el}$: Width, thickness of the electrodes. $XeF_2$: Xenon difluoride.*

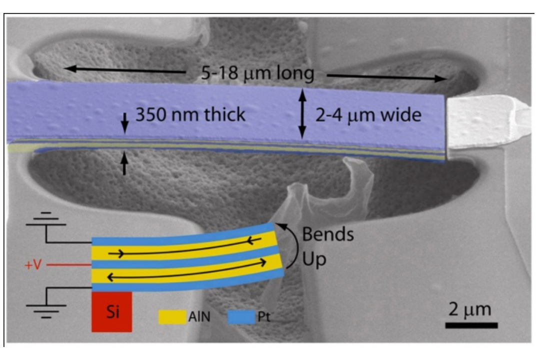



Figure 2. SEM and schematic diagram of a bimorph actuator formed by two 100nm-thick layers of AlN and three 50nm platinum (Pt) electrodes. Si: Silicon. +V: Power supply

### 4.1.2 Nanopositioning

Nanopositioning systems with nanometer level resolution and accuracy are important for micro- and nanotechnology. Nanopositioning stages are widely used in various applications, such as scanning probe microscope, optical alignment, micro-/nano manipulation and micro/nano manufacturing. The majority of current nanopositioners use slow mechanical strain based structures. A high natural frequency is a critical requirement for nanopositioners in high-throughput nanomanufacturing and nanometrology applications. Most nanoscale manipulators and manufacturing processes require extremely fast speed. Fast manipulation processes place increasingly demanding performance requirements on nanopositioning systems. The slow response speed of nanopositioners becomes a bottleneck for achieving high-rate nanomanufacturing and nanometrology (e.g., high-speed imaging). A high-speed nanopositioning system can significantly increase the manipulation and manufacturing efficiency. High precision and high accuracy are also essential for nanoscale manipulation and manufacturing. The high-speed nanopositioner is expected to address applications such as high-throughput nanoscale metrology, imaging, and manufacturing.

### 4.1.3 NEMS Apparatus in NEMS Robotic Assembly

A NEMS contains elements of nanoelectronics, such as a system on a chip semiconductor device, within a larger structural casing. The nanoelectronic system includes computer logic circuits  and memory circuits. These electronic components are connected to other nanoelectronic parts, including a communications system consisting of a processing element and antennae for wire or wireless transmission and reception, sensors, an actuator, a motor, a power source and specific on-board mechanical or electromechanical parts that have specific functionality, such as gears, shielding, cargo space, valves or pumps.

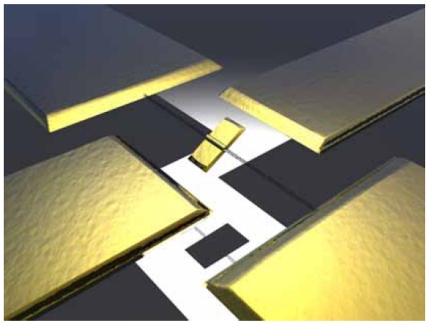
### 4.1.4 Nano-RF Repeaters for Communications

Because communications resource constraints are significant at the nano-scale, NEMS require distinctive architectures. NEMS have a limited communication range, which makes the use of a distributed system of groups of NEMS critical when specific NEMS communicate at a limited range to their closest neighbor. Although such distributed network architectures use node-to-node message passing procedures, it is still necessary to amplify communications signals in this distributed NEMSic system.

The present system provides a novel way to bounce signals from position to position so as to extend the range of a signal. The system involves the use of NEMS as repeaters to temporarily amplify and bounce communication signals beyond the range of a single node. For instance, when a series of NEMS is arranged in a sequence of nodes, the

NEMS successively receive and retransmit the signal to their neighbors. Because the system is mobile, in some cases the NEMS will temporarily rearrange geometric position (by using mobility) precisely in order to behave as a repeater assembly system so as to transmit signals.

### 4.1.5 Synthetic Molecular Motor



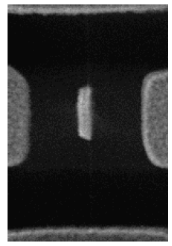


Figure3-3. Example of Hybrid Fabrication. *Left*, schematic of molecular motor. *Right*, SEM image of the working motor. A 250-500 nm rotor was suspended on a double-walled carbon nanotube (the atomically precise part in the assembly). Electrodes were lithographically fabricated on either side of the rotor, underneath the rotor (not shown), and around the ends of the nested nanotube. Varying the voltage differences between electrodes caused the rotor to spin. *Courtesy Zettl Research Group, Lawrence Berkeley National Laboratory and University of California at Berkeley.*

*3.5.1 Zettl Group: Synthetic Molecular Motor*

### 4.1.6 Hybrid MEMS and NEMS

The present system integrates NEMS parts into MEMS robotic structures. NEMS components, such as nano-scale chip sets, are integrated into MEMS assemblies as microelectronic systems become increasingly smaller. It is not unusual, then, to have NEMS parts integrate with other systems, including not only microelectronics but photonic systems and mechanical systems as well. Optoelectronic systems require NEMS parts as their utility involves ever smaller components. An example of this system integration is the use of nanofilaments in MEMS communications devices in which the filaments provide simple RF antennae or nanoelectronic parts such as nanotransistors. Similarly, nanooptoelectronic mechanical (NOEMS) systems are integrated with MEMS assemblies in order to maximize the benefits of both.

### 4.1.7 Computing Applications

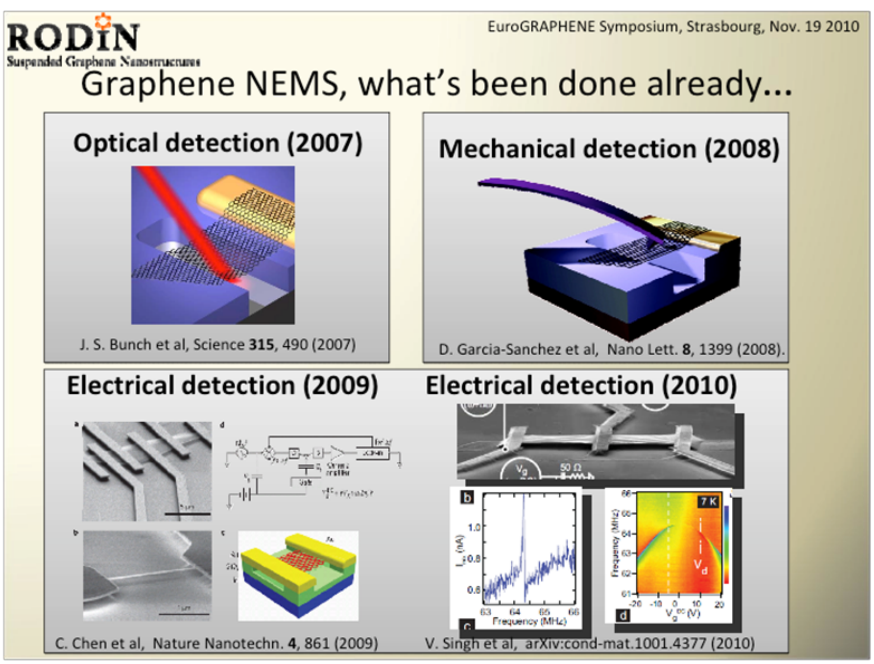
Another application to be considered is s Quantum computers that will provide faster computing times to enable the efficient optimization of nano-materials properties through simulation and modeling. Chips that have both vertical and horizontal connections, to pack in more computing power while using less power requiring less frequent recharging. Which goes along with developing energy-efficienc customizable chips for mobile devices.

### 4.1.8 Tunable RF-Resonators

Mobile phones are using more bandwith with mobile computing, gaming, and enternainment consumption added to talk and text features of the phone. Data traffic is growing rapidly and the available bandwith is limited. The single device should be able to operate at several frequency bands. A potential solution would be to develop a cognitive radio that could find available bandwidths using reprogrammable filters and reference oscillators. This would lead to developments in low power RF communications, sensing, and signal processing.

### 4.1.9 Self-Sensing Cantilevers

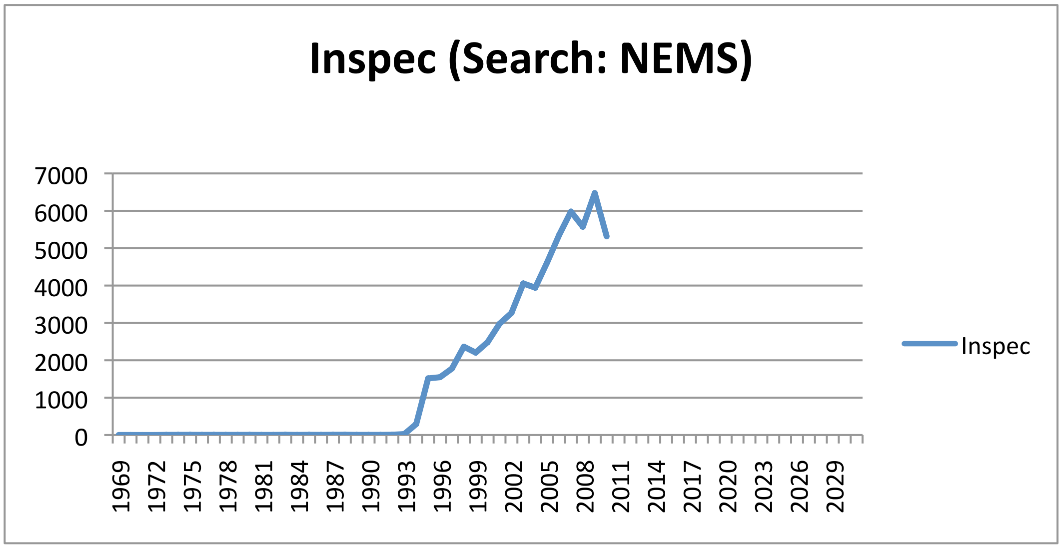
Silicon nanoscale cantilevers enable important applications such as atomic force microscopy (AFM) and biological force spectroscopy. Most efforts in this area employ cantilever probes with external displacement transduction via off-chip sensing systems. These systems are typically optically-based, involving simple optical beam deflection or more sensitive interferometry. Self-sensing cantilevers, which possess integrated displacement transducers, offer important advantages that are not attainable with external optical methods. Perhaps most promising are: scalability to extremely small cantilever dimensions, below an optical wavelength and, thereby, to very high frequencies; measurement without optical perturbation of susceptible samples; suitability for large-array technologies and portable sensing; and ease of applicability to multiple-cantilever sensors that permit correlated or stochastic detection. Furthermore, use of on-chip electronic readout is especially advantageous for detection in liquid environments of low or arbitrarily varying optical transparency, as well as for operation at cryogenic temperatures where maintenance of precise optical component alignment becomes problematic.

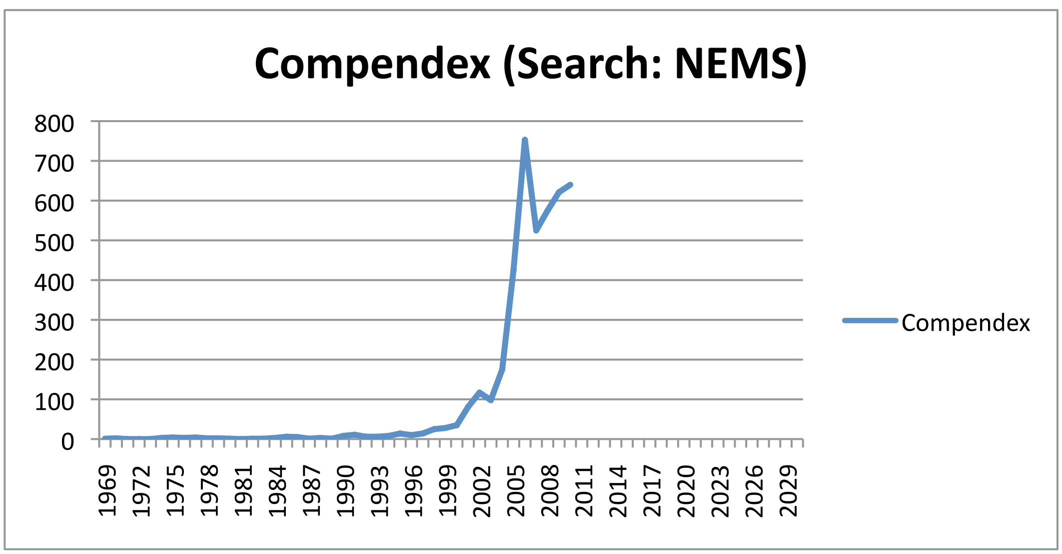


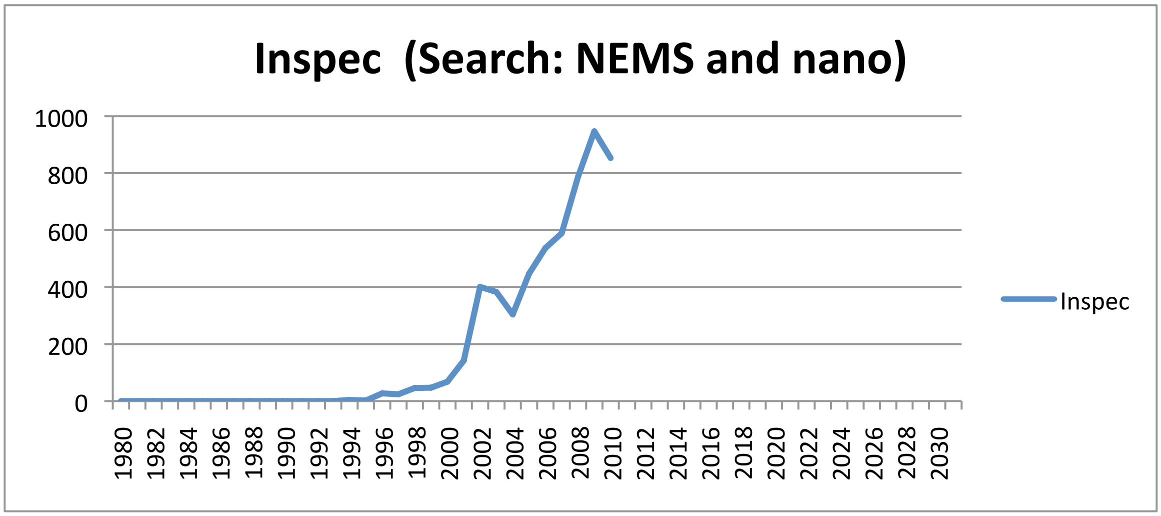
The important take-away from these applications listed in section 4.0 is that even though there are no massively commercialized NEMS products, the foundational science and technology is being proven through prototypes and lab scale experiments. This is the first step in achieving the potential of NEMS.

## 5.0 What is the current state of the technology

### 5.1 Bibliometrics

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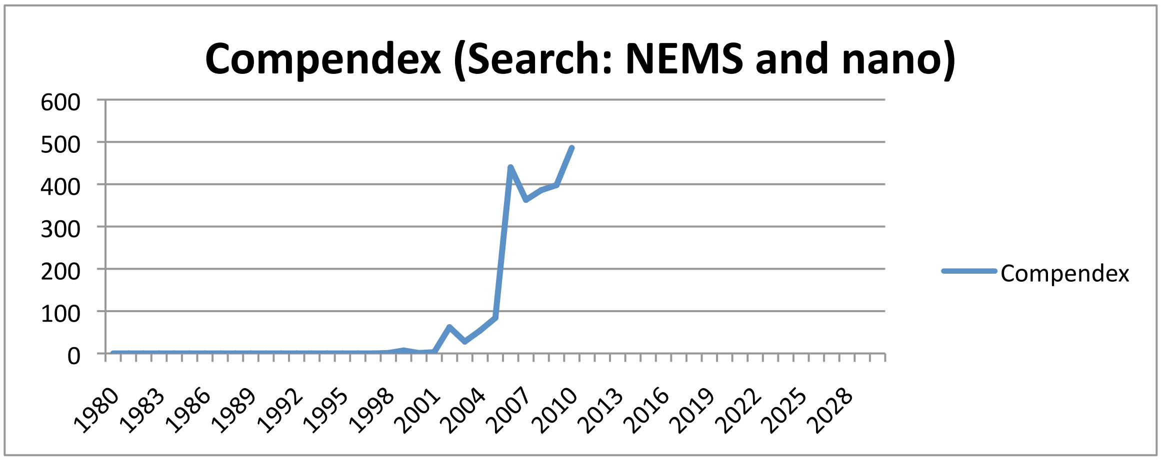
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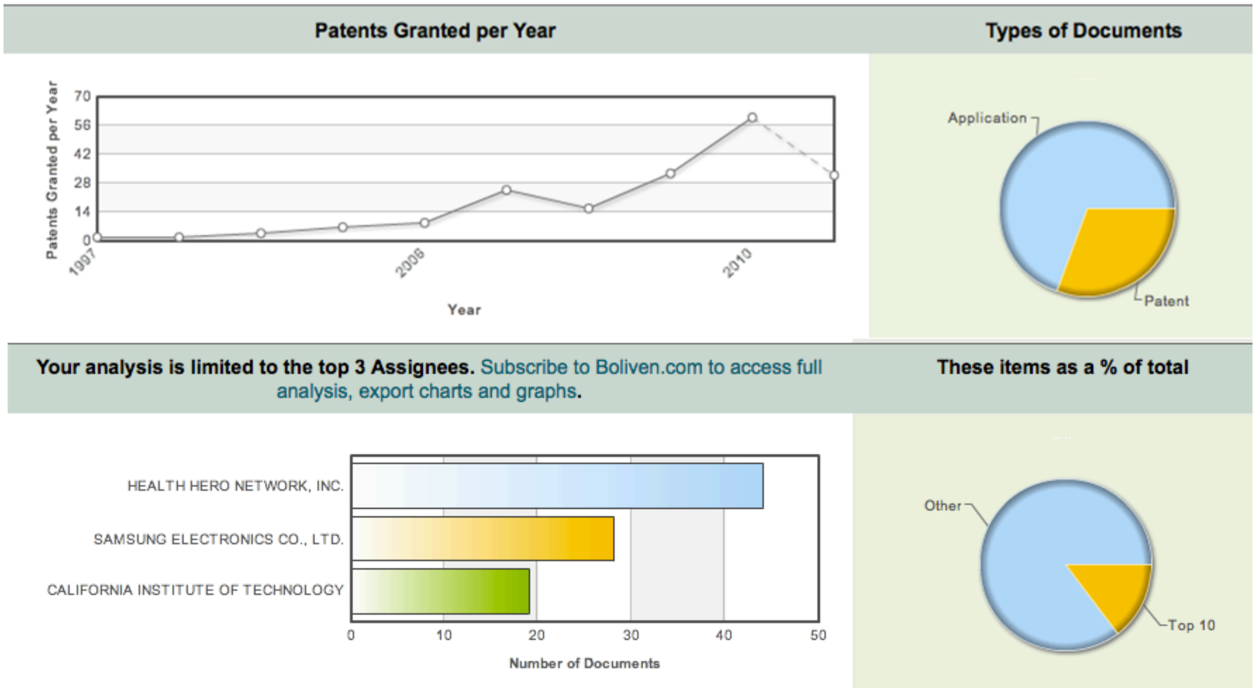
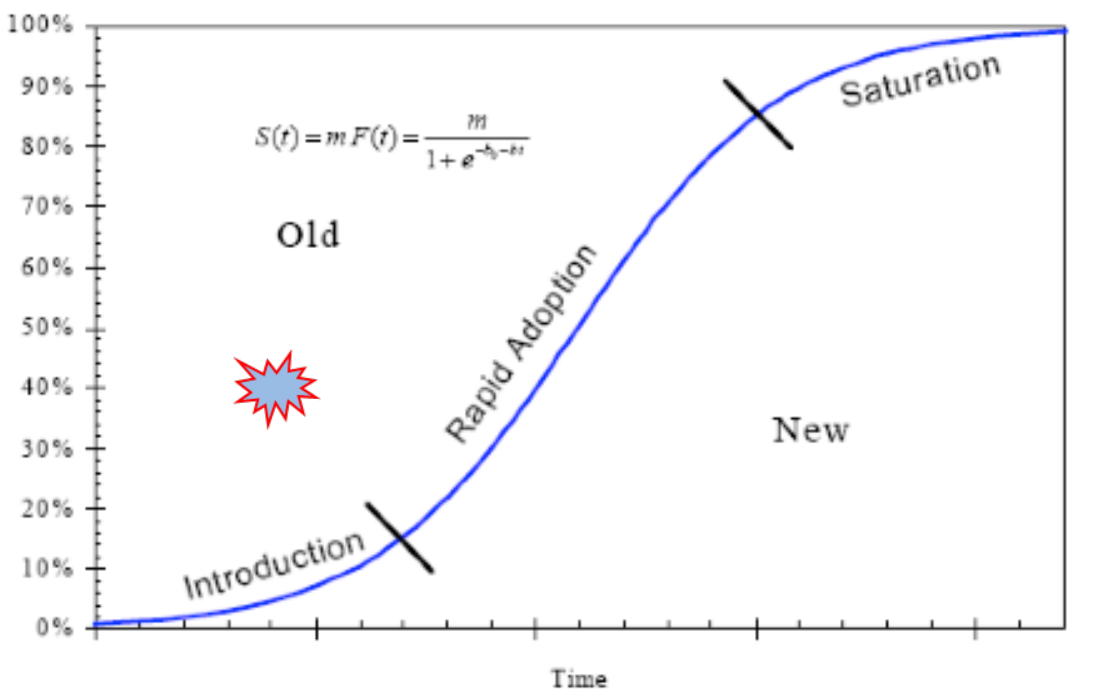
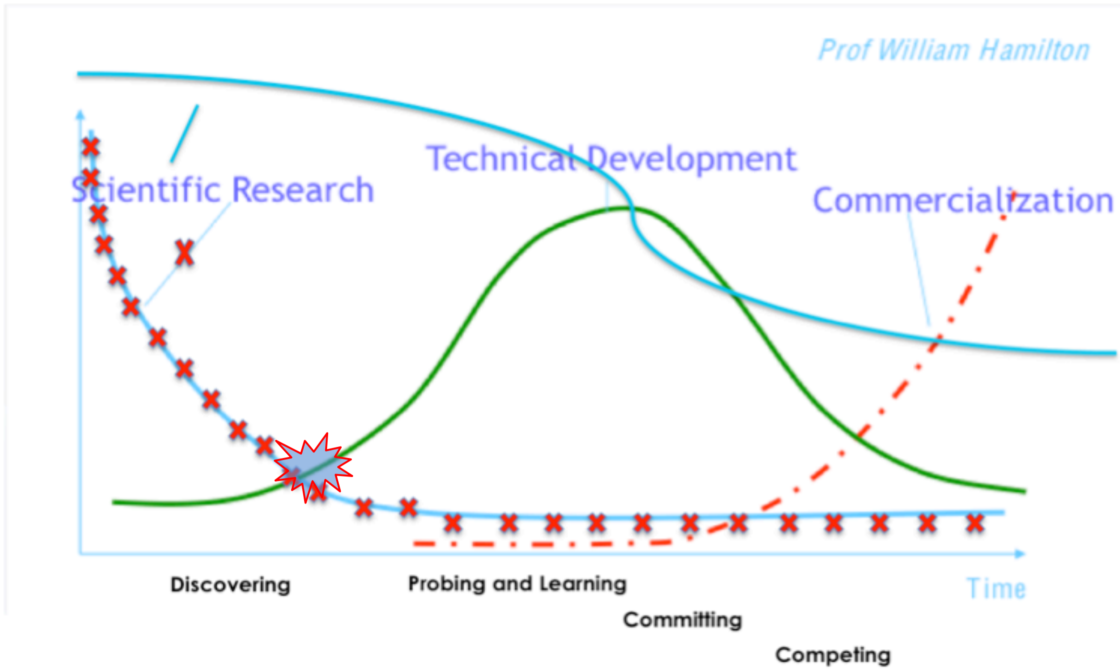
## 5.2 Patents




## 5.3 Maturity Models for NEMS as an Emerging Technology




**Maturity Model**




**Hamilton's Emerging Technology Model**

## 6.0 Who the major players

**Academic Research Centers**

California Institute of Technology, The University of Illinois at Urbana-Champaign, Purdue University, The Georgia Institute of Technology, Cornell, MIT, Northwestern University, UC-Berkeley, Stanford …

**Electronics Industry**

Samsung, Nokia, MEMtronics, Toyota, HP, Bosch, Pansonic, WiPro, Imec, Nanosys, Nanometrics, Intel, QualComm, Applied Nanotech, Nanorex, Global Foundaries …

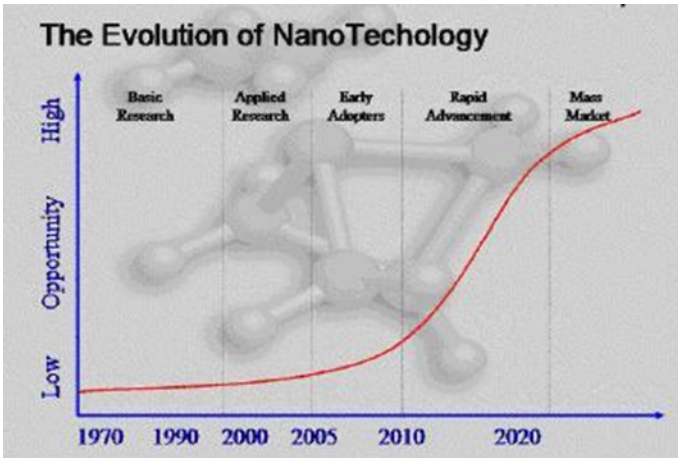
**Biomedical Industry**

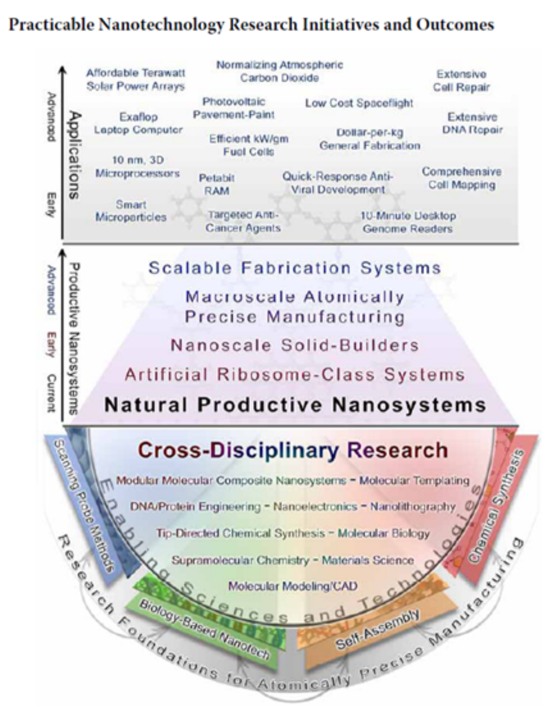
Abbot Labs, Boston Scientific, Pelikan Technologies …

**National Research Labs**

DARPA, Sandia, Lawrence Livermore + COINS, NASA, NIST, Los Alamos …

## How will it be commercialized, and by which major players




Credit E. Drexler

## 7.0 What are the risks and difficulties of implementation?

### 7.1 What is needed for commercializations

To bring NEMS into the mainstream, the emergent industry needs a flexible, low-cost, fast, and simple manufacturing alternative to the largely laboratory scale methods currently used. The foundational technology should be broad enough to fabricate many different types of structures, and it should be compatible with CMOS semiconductor technology. There also needs to be plenty of funding and champions in industry and academia pushing the development of NEMS technology.

### 7.2 What are the Risks and Challenges

There are a lot of challenges to the big ideas of NEMS. The main challenge is that the fundamentals of nanotechnology are still being worked out. There may be something like a critical tipping point, when enough experimenting has been done, and enough data has been collected to provide the groundwork for rapid developments, and the solutions to the problems of today will be common knowledge in the field. The intricacies of quantum mechanics are not well known, so there is a lot of learning in this new design space. There is interference at the molecular level, there is stiction and temperature limits, and many other limitations. The manufacturing of nanoparts is difficult, and so is the assembly of nanoparts into functional devices. The control and management of nanosystems is very complex. Physical properties operate differently at the nano-scale than at the macro-scale, and these differences need to be constantly considered when design systems.

Once the science is figured out there is a whole range of additional challenges. Meeting industry specifications; which involves knowing all of the technical specifications involving specific properties like Q-Factor, impedence, thermal stability, to production standards like fabrication tolerances, reproducibility and quality. Clear communication between industry and academia can be a problem, and this must be established at the earliest stages of development projects.

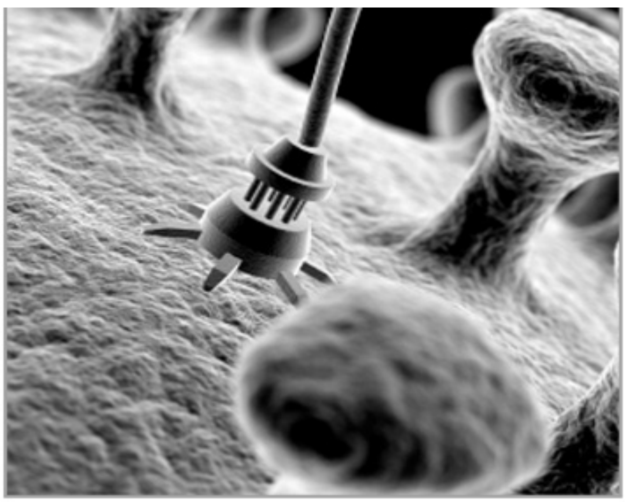
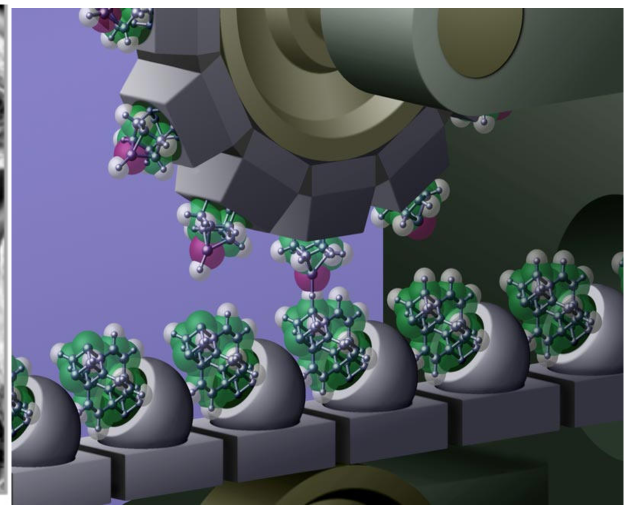
Achieving reproducible properties and results is a challenge in any early stage development, and this problem is exacerbated at the nano level because there is added error from measuring equipment and techniques

Fabrication and manufacturing techniques need to be transitioned from the lab scale to the manufacturing scale. Lab prototypes need to be highly reproducible.

Standard change will make existing products obsolete. There will also be interface issues and these new revolutionary devices my not be compatible with existing technologies which will render them useless unless peripheral technologies quickly emerge to support them. Another Major risk is losing touch with reality and disciplined imagination. It is easy to get carried away with science fictional functionalities of NEMS, but these ideas need to be grounded in reality.

There are additional Risks with health and environmental concerns of nanotechnology.

Nanotechnology is "long on vision and short on specifics"

Credit E. Drexler

## 8.0 CONCLUSIONS

By 2026, there may be an adoption of NEMS devices at the level one now finds MEMS systems. Functional NEMS devices may include: highly functional sensors, noninvasive medical diagnostic devices, nanoresonators with direct consequences for the wireless communication technologies, significant increase in battery life for mobile electronics and ultrahigh-density data storage systems. The basic studies of fabrication approaches and the science of nanoscale systems are taking place now.

Emerging NEMS might accelerate the development of novel MEMS. Integrated systems from NEMS and MEMS might be of high relevance (such as MEMS sensors with NEMS as core components), analogous to living cells (microscaled), with many higly organized and functional nanoparts as components. It might be possible to produce a system comprised of both NEMS and MEMS where the limitations of MEMS can be solved with NEMS components and the limitations of NEMS could be solved with MEMS components. **E**ven though there are no massively commercialized NEMS products, the foundational science and technology is being proven through prototypes and lab scale experiments. This is the first step in achieving the potential of NEMS.

To commercialize NEMS it will be important to leverage the successes of MEMS technology and hybridize with NEMS with MEMS to prove the capabilities of NEMS. Research needs to be continued to mature the technology. Prototypes and capability studies will need to be pursued, and manufacturing will need to be scaled up, with the goal of high quality reproducibility. Clear communication between industry and academia must be established at the earliest stages of development projects. Another Major risk is losing touch with reality and disciplined imagination. Inventors must not get carried away with science fictional functionalities of NEMS, but these ideas need to be grounded in reality.

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