# Roadmapping Convergence


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### WHAT IS A ROADMAP?

A roadmap describes a future environment, objectives to be achieved within that environment, and plans for how those objectives will be achieved over time. It lays out a framework, or architecture, as a way of understanding how the pieces of a complex technological system fit together, interact and evolve. It links applications, technical challenges and the technological solutions together, and it helps set priorities for achieving the objectives.

### WHAT IS ROADMAPPING?

The best roadmaps are created as a team activity, receiving the views and knowledge of the group of people who will carry out the roadmap's plan. The roadmapping process helps a team gather diverse perspectives on all aspects of the environment and the plan. It also helps the team build consensus and gets buy-in of its members to carry out the plan. Roadmaps also are the basis for the team to describe their objectives and planned actions to customers, suppliers, and stakeholders.

### ROADMAPS FOR CONVERGING TECHNOLOGIES

The uncertain, cross-disciplinary environment of emerging advanced technologies such as nanotechnology, biotechnology, information technology and cognitive science makes for very complex planning situations. Application needs may be satisfied by many possible combinations of technologies, and understanding the tradeoffs in a search for a solution can be difficult. Roadmaps make the description of the situation and linkages from application to technology explicit, allowing an informed decision process and providing a tool for communicating the chosen direction and monitoring progress along the way.

There are many questions teams might seek to answer about the future of the converging technologies. What inventions will be practical enough to become innovations, and when? How will the fields interact to produce innovations? What customer and market drivers and development actions will be needed for commercialization? What are gating factors to innovations and how can they be satisfied? What are the risks to innovation?

Roadmapping provides a framework to answer these and other questions. The scope of converging technologies is so broad that we must define manageable sub-areas to apply roadmapping methods to understanding and plotting a future direction. This paper describes a roadmap structure, some key elements of the structure, and provides some examples that will help in steering towards meaningful convergence roadmaps.

### A COMMON FRAMEWORK FOR ROADMAPS

Roadmaps lay out a future objective and answer a set of "why-what-how-when" questions to develop an action plan for reaching the objective [2, 5]. Figure 1 describes the four parts of the roadmap architecture that answer the "why-what-how" questions and lay out required actions, the "to-do's."

The first part defines the domain of the roadmap, the team's objectives, and their strategy for achieving those objectives – the "why" of a roadmap. The roadmap's definition and strategy often include market and competitive assessments as well as planned applications. The second part defines direction, or the team's plans – the "what" of a roadmap. The direction includes challenges, the architecture and evolution of the team's solution, and measurable performance targets to achieve the objective. The third part describes the evolution of technologies that will be used to achieve the objective – the "how" of a roadmap. The "technology roadmap" defines the technologies that will be used to implement each part of the architecture. The fourth part defines the action plan and risks – the "to-do's" of a roadmap. The action plan identifies key development actions, resources required, risks, and technology investment strategy. All parts of the roadmap are laid out over time – the "when" of a roadmap.


**Figure 1. A unifying four-part roadmap framework**

A roadmap may be constructed beginning with the key needs of the marketplace and customers – a market-pull perspective. Conversely, a roadmap may start with a key technology and seek to define the market needs that could be served with the new technology – a technology-push perspective.

## OBJECTIVES AND FORMATS FOR ROADMAPS

Within the four part architecture, the contents of roadmaps with the most frequently encountered objectives are outlined in Figure 2. The figure lists the topics covered in each of the four parts of a roadmap for several types of roadmaps. Science and technology roadmaps plot the future development of a scientific or technical field. The scope of the scientific field and current or potential applications of the technology are linked to key technical challenges of the field. The structure, or architecture of the field is defined and trends and potential discontinuities are identified. The challenges are then linked to the evolution of the field in the technology roadmap. Finally, action plans for resource allocation or investment are defined to achieve the most important technological developments. Industry/government-sponsored roadmaps aim to describe the future of an industry or sector along with actions to move the industry or sector forward. Industry structure and key directions are linked to technical challenges and those challenges are linked to technology evolution. Corporations and other organizations use roadmapping for a number of purposes such as product planning, platform planning, or organizational capability planning. Product-technology or platform roadmaps lay out the evolution of a product or platform over time. Capability roadmaps define the capabilities needed for success of a services business or for functional organization such as manufacturing or information technology.

| | Definition and Strategy "Know-why" | Direction "Know-what" | Technology "Know-how" | Action Plan "To-do" |
|---|---|---|---|---|
| **Science and Technology Roadmaps** | • Scope of the Field<br>• Technology Applications | • Technical Challenges<br>• Architecture<br>• Trends, Discontinuities, and Objectives | • Technology Elements and Evolution<br>• Competitive Technologies and Costs | • Action Programs<br>• Technology Investment<br>• IP and Standards<br>• Risk Roadmap |
| **Industry and Government Roadmaps** | • Industry Structure and Position<br>• Customer Drivers<br>• Industry Direction | • Technical Challenges<br>• Architecture<br>• Trends and Disruptions<br>• Learning and Targets | • Technology Elements and Evolution<br>• Technology Alternatives<br>• Future Costs | • Action Programs<br>• Technology Investment<br>• IP and Standards<br>• Risk Roadmap |
| **Product – Technology and Platform Roadmaps** | • Market Structure and Size<br>• Customer Drivers<br>• Competitive Strategy | • Product Roadmap<br>• Architecture<br>• Product Drivers and Targets<br>• Feature evolution | • Technology Elements and Evolution<br>• Competitive Position<br>• Target Costing | • Action Programs<br>• Technology Investment<br>• IP and Standards<br>• Risk Roadmap |

**Figure 2. Roadmapping Topics**

## SCIENCE AND TECHNOLOGY ROADMAP

Figure 3 shows a typical layout of templates for a roadmap, in this case a Science and Technology Roadmap. The template in Figure 3 includes four parts as defined above. The first part, the definition and scope, covers market and competitive strategy. The second part defines the product direction, the product roadmap. The third part defines the technology evolution, the technology roadmap. Finally the action plan defines the key programs or projects that will be needed to support the direction, a technology investment summary, and a view of the risks to the plan. Each part is elaborated in a series of pages or panels describing an important element of the plan. The four parts are linked by connecting drivers – customer drivers to product drivers to technology elements to technology investments. In this way the rationale for decisions on directions taken may be tracked in order to conduct a structured review of gaps and develop plans for closing those gaps.

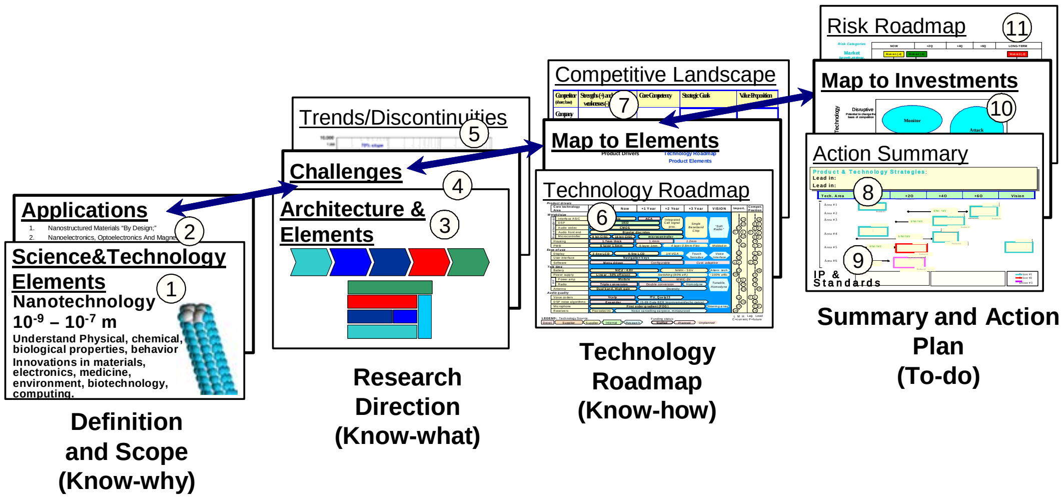



**Figure 3. The four parts of a Science and Technology Roadmap**

## SCOPE AND DEFINITIONS

The first step in roadmapping is to define the scope. At the highest level, we can begin with some draft definitions of the scope of converging technology fields.

- Nanotechnology: Technology related to features of nanometer scale ($10^{-9}$ meters): thin films, fine particles, chemical synthesis, advanced microlithography, and so forth
- Biotechnology: The application of science and engineering to the direct or indirect use of living organisms, or parts or products of living organisms, in their natural or modified forms.
- Information Technology: Applied computer systems - both hardware and software, including networking and telecommunications.
- Cognitive Science: The study of intelligence and intelligent systems, with particular reference to intelligent behavior as computation.

## BENEFITS OF ROADMAPPING

In roadmapping, a team is concerned with understanding and planning for *innovations*, defined as "the introduction of something new." For our roadmapping purposes, this is taken to mean new technology put into practice and widespread use. A technology may be invented, but will not be an innovation until widely applied.

Roadmapping should help teams answer questions such as: How will fields interact to create innovations? What innovations will occur and when? What is needed to create innovations? What are gating factors for innovations?

There are many efforts underway, and many more will come, to plan and roadmap within each of the technology fields. We should focus our roadmapping in two areas. First, we should look where innovations occur at the intersections of fields. For example, at the nano-scale, nanotechnology and biotechnology will often be indistinguishable. Second, we should look to innovations in one area that will be enabled by innovations in another. For example, as biotechnology becomes more information intense, it will be enabled by information technology.

## KEY ELEMENTS OF A CONVERGENCE ROADMP

Three key supporting elements of a roadmap are applications/needs, architecture, and growth trends.

*Applications* or customer/market needs determine drivers for the roadmap. Drivers are usually of the following types: "Do more," "do for less," "do new things," "do enabling things." Applications are often expressed in grand challenges for the field. For example the table below lists the Grand Challenges for the US National Nanotechnology Initiative:

| NNI Grand challenges (2001) |
|---|
| • Nanostructured Materials "By Design;" |
| • Nanoelectronics, Optoelectronics And Magnetics |
| • Advanced Healthcare, Therapeutics And Diagnostics |
| • Nanoscale Processes For Environmental Improvement |
| • Efficient Energy Conversion And Storage |
| • Microcraft And Robotics |
| • Nanoscale Instrumentation And Metrology |
| • Manufacturing At The Nanoscale |
| • Nanostructures for Chemical, Biological, Radiological, and Explosive (CBRE) Detection and Protection |

The next table lists Grand Challenges in Global Health defined by the Foundation for NIH in October, 2003.

GOAL: To improve childhood vaccines:
GC#1 Create effective single-dose vaccines that can be used soon after birth;
GC#2 Prepare vaccines that do not require refrigeration;
GC#3 Develop needle-free delivery systems for vaccines.

GOAL: To create new vaccines:
GC#4 Devise reliable tests in model systems to evaluate live attenuated vaccines;
GC#5 Solve how to design antigens for effective, protective immunity;
GC#6 Learn which immunological responses provide protective immunity.

GOAL: To control insects that transmit agents of disease:
GC#7 Develop a genetic strategy to deplete or incapacitate a disease-transmitting insect population;
GC#8 Develop a chemical strategy to deplete or incapacitate a disease-transmitting insect population.

GOAL: To improve nutrition to promote health:
GC#9 Create a full range of optimal, bioavailable nutrients in a single staple plant species.
GOAL: To improve drug treatment of infectious diseases:
GC#10 Discover drugs and delivery systems that minimize the likelihood of drug resistant micro-organisms.

GOAL: To cure latent and chronic infections:
GC#11 Create therapies that can cure latent infections;
GC#12 Create immunological methods that can cure chronic infections.

GOAL: To measure disease and health status accurately and economically in developing countries:
GC#13 Develop technologies that permit quantitative assessment of population health status;
GC#14 Develop technologies that allow assessment of individuals for multiple conditions or pathogens at point-of-care.

*Architecture* defines how the pieces of the problem fit together. The architectural elements become the framework for the technology roadmap and help determine the priorities of work to achieve the roadmap's objective. An architecture for roadmapping convergence was suggested by discussion at the *Convergence Commercialization Workshop* at US National Science Foundation, September 22, 2003 and is shown in Figure 4.

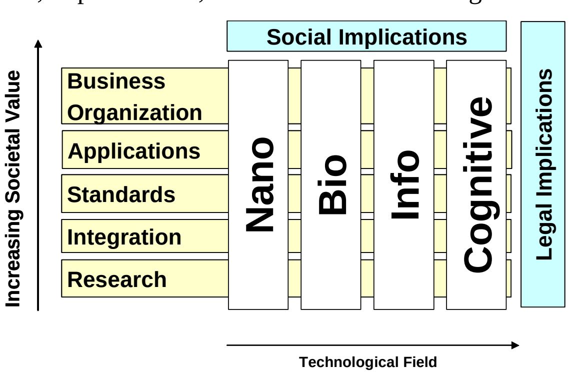



**Figure 4. Architecture for Convergent Technologies**

*Growth trends.* Identification of long term, sustained growth trends is central to understanding which inventions can become innovations. Trends in enabling technology result in continued declining costs for technology applications and increasing sophistication of applications.

Declining costs of technology allow increasingly complex applications. These trends have been apparent in information technology for more than 40 years. For example, Figure 5 shows the exponential growth of computing power that began in the 1940's and continues at the present.

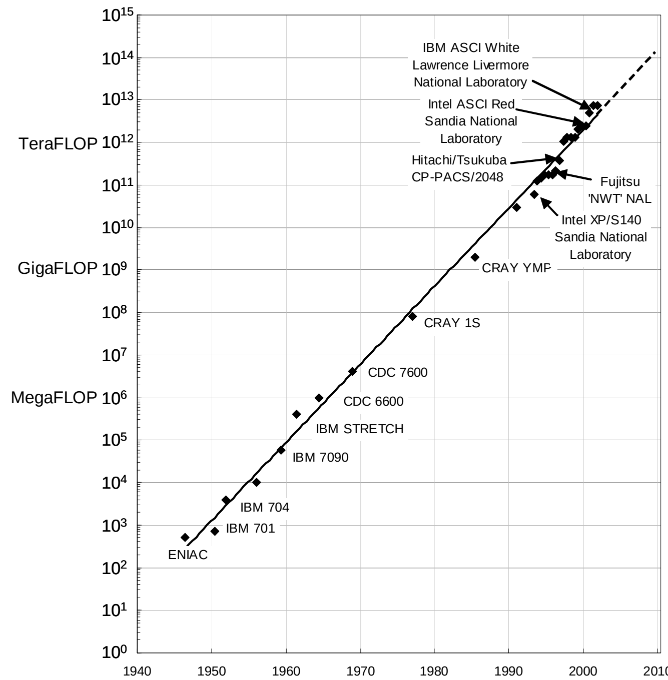


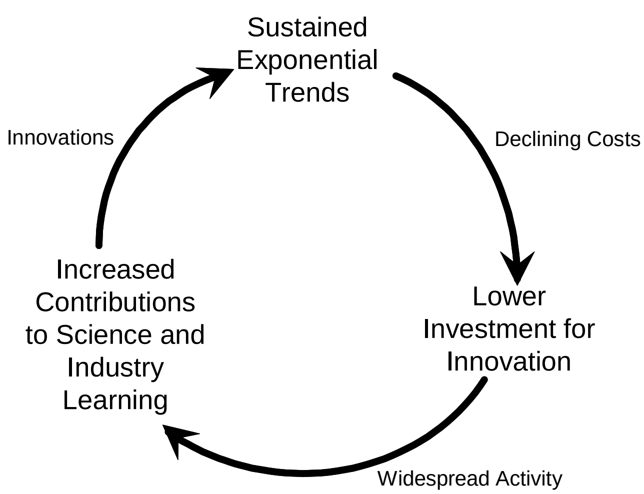

**Figure 5. The power of the fastest computers has grown exponentially since the 1940's**

Declining semiconductor costs enable applications using greater amounts of stored data and more complex algorithms for processing. For example, steady increases in the abilities of chess playing computers tracked the advances of the fastest computers of the day to the point that computers now compete at the highest level. Voice processing, a complex processing challenge, is becoming practical in compact, often portable electronics with the use of low cost memory and digital signal processing. Lower cost electronic processing is also replacing mechanical functions in automobiles and other large equipment.

Information technology trends are well established and are widely tracked and used for forecasting. The ten year forecast of needed capabilities of the International Technology Roadmap for Semiconductors is updated every two years. Many of the same information enabling technologies will apply to fabrication of nanoscale devices, although we must look for new exponential power and cost trends. In biotechnology, the exponentially declining cost of genetic sequencing has been active for about ten years, and appears to have many more decades of improvement. Semiconductor technology is also a driver for genetic analysis as chips for DNA and protein analysis are developed.

Cognitive science is the most problematic of convergence areas where trends are concerned. The problems of Cognitive and brain science are ones of how to accomplish goals – understanding the processes that are taking place – rather than the speed or number of steps. For example, the promise of artificial intelligence has not been advanced to the extent hoped by increased processing power. Results are more a function of algorithms and understanding of complex cognitive skills.

*Positive innovation loop*. Lower capital requirements allow more people to use the technologies for innovation. The lower costs of enabling technologies allow more people to be involved and to collaborate in new ways. This positive innovation loop is shown in Figure 6. The innovations of many technology start-up corporations are possible due to lower costs and reduced financial risks. The open source movement in software development that emerged in the 1990's has been enabled by low cost, widely available global communications of the internet, low cost powerful computers, and widely available software – allowing rapid contributions to innovative software systems and rapid application and improvement by many individuals.




. **Figure 6. Sustained technology trends lower investment, creating a positive innovation loop.**

## MOVING FORWARD

To prepare to move ahead with roadmapping for converging technologies, teams should work in three areas, defining applications and related technology areas, identifying trends, and refining architectures.

An important next step toward creating roadmaps for converging technologies is identification of areas where there is important interaction among the fields. An example based on the application sets presented earlier is shown in Figure 7. In the figure, the four technology convergence fields are mapped to applications (challenges), showing where the intersections and enabler will likely be found. The technology fields could be further segmented, and the applications could be further filled out. The technology segmentation could form the basis of an architecture for a set of technology roadmaps that show how the applications can be implemented.

A systematic analysis of trend areas can begin with information technology, where the trends are well understood, and then move into nanotechnology and biotechnology trends.

With supporting information developed, a roadmapping team can define the scope of the roadmap they seek to create along with a set of objectives. They then can develop a roadmap to realize their objectives.

| Figure 7. Application Mapping to Technology Fields | | | | |
|---|---|---|---|---|
| **Application** | **Nano technology** | **Bio technology** | **Information Technology** | **Cognitive Science** |
| **NNI Grand challenges (2001)** | | | | |
| Nanostructured Materials “By Design;” | X | | | |
| Nanoelectronics, Optoelectronics And Magnetics | X | | X | |
| Advanced Healthcare, Therapeutics And Diagnostics | X | X | | X |
| Nanoscale Processes For Environmental Improvement | X | | | |
| Efficient Energy Conversion And Storage | X | | X | |
| Microcraft And Robotics | X | | X | |
| Nanoscale Instrumentation And Metrology | X | | X | |
| Manufacturing At The Nanoscale | X | | | |
| Nanostructures for Chemical, Biological, Radiological, and Explosive (CBRE) Detection and Protection | X | X | X | |
| **Grand Challenges: Foundation for NIH (10/2003)** | | | | |
| GOAL: To improve childhood vaccines: | | | | |
| Create effective single-dose vaccines that can be used soon after birth; | X | X | | |
| Prepare vaccines that do not require refrigeration; | X | X | | |
| Develop needle-free delivery systems for vaccines. | X | X | | |
| GOAL: To create new vaccines: | | | | |
| Devise reliable tests in model systems to evaluate live attenuated vaccines; | | X | X | |
| Solve how to design antigens for effective, protective immunity; | X | X | X | |
| Learn which immunological responses provide protective immunity. | | X | X | |
| GOAL:To control insects that transmit agents of disease: | | | | |
| Develop a genetic strategy to deplete or incapacitate a disease-transmitting insect population; | | X | X | |
| Develop a chemical strategy to deplete or incapacitate a disease-transmitting insect population. | X | X | | |
| GOAL: To improve nutrition to promote health: | | | | |
| Create a full range of optimal, bioavailable nutrients in a single staple plant species. | | X | X | |
| GOAL: To improve drug treatment of infectious diseases: | | | | |
| Discover drugs and delivery systems that minimize the likelihood of drug resistant micro-organisms. | X | X | | |
| GOAL: To cure latent and chronic infections: | | | | |
| Create therapies that can cure latent infections; | X | X | X | |
| Create immunolgical methods that can cure chronic infections. | X | X | X | |
| GOAL: To measure disease and health status accurately and economically in developing countries: | | | | |
| Develop technologies that permit quantitative assessment of population health status; | | X | X | |
| Develop technologies that allow assessment of individuals for multiple conditions or pathogens at point-of-care. | | X | X | X |