# Web-based Survey of Trends in Dematerialization

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## Scope of Work

This research is a web-based survey of information and data trends on the topic of dematerialization. Eco-efficiency, industrial ecology and dematerialization-related developments in nanotechnology were investigated. References for data and information are provided throughout the following document. As this research was an assessment of trends in dematerialization, information and data points gathered from companies and trade associations were included without evaluating or verifying the claims.

This assessment is a review of company and industry best practices of dematerialization. Analysis has illustrated clear candidates for reducing material intensities. It has also shown that some products and processes have hidden material and energy flows that can impact the extent to which dematerialization actually occurs. To more effectively assess the benefits of dematerialization strategies requires a more detailed assessment of different spatial scales – from the product and process level to the company and sector level. There is also a need to assess the pollution, wastes, energy requirements, and natural resource requirements within each scale. Such a critical analysis looks not only at the amount of natural resources contained in assessed commodities and products, but also the hidden flows which are involved in producing them. Assessing the entire life cycle of a product can help to understand the systemic effects of different materials in different applications and the quantities of material inputs, thus providing information on the direct and indirect efficiencies of resource use.

## Trends in Dematerialization

The word dematerialization has been defined in this review of company practices to characterize the decline over time in weight of the materials used in industrial end products as well as changes in production processes that result in a reduction of material throughput.

The trend toward dematerialization is being primarily driven by four factors:

- *First*, the cost of producing materials has been increasing, largely because materials processing tends to be energy-intensive.
- *Second*, there is increasing competition from substitute materials, many of which are lighter and have superior properties to basic materials such as steel. This results in substitution of materials with lower mass, or in the introduction of specialty versions of basic materials, which give improved performance with less mass for the same function. An example is the increasing use of high-strength steels in automobile manufacturing
- *Third*, some materials seemingly have saturated the markets for their bulk use. Just as the major uses of steel and cement have been in the construction of infrastructure that is largely complete in industrialized countries, the market for cars and consumer durables per capita is also close to saturated, consisting primarily of replacement demand.
- *Fourth*, following on the third point, discretionary income now tends to be spent on goods and services with lower materials content per consumer dollar. [1]

The ultimate dematerialization example is the integrated circuit, where the packing density has increased exponentially since 1960. Cars have also become lighter on average, although the recent sales growth of light trucks and sport vehicles counters this trend. The automobile is an interesting object for study because it represents a full market basket of the products of an industrialized economy, including metals, plastics, electronic materials, rubber, and glass.

## Dematerialization in the Automobile

**PNGV**[2]

The Partnership for a New Generation of Vehicles (PNGV), has a goal to a develop a vehicle with up to three times the fuel economy of today's conventional, mid-sized sedans, while achieving improved recyclability and maintaining comparable performance, utility, safety, and cost of ownership.

PNGV research efforts had included:

Polymer Composites

- Structural Reaction Injection Molding (SRIM) process demonstrated for automotive underbody crossmember. Process has potential to support high-volume automotive production.

Aluminum

- Continuous slab casting, which has potential to substantially lower cost, has been used to manufacture automotive-grade sheet metal material for fabrication trials. Also, recent medium/ high volume production of an aluminum body panel has added to confidence in forming, joining, and painting of aluminum.

Steel Space-Frame Vehicle Structure

- Conceptual design completed, but significant challenges remain. Some feel this concept has the potential for 50% weight reduction while reducing both manufacturing and tooling costs compared with conventional unitized steel body structure.

**Steel**

Steel is the dominant automotive material, accounting for 55% the mass of an average 1997 family vehicle, in large part because it's inexpensive per kilogram, strong and stiff, and relatively predictable and manufacturable. Steel enjoys the benefits of incumbency, such as industry familiarity and extensive manufacturing infrastructure. However, steel is heavy, capital-intensive, and slow to tool— tooling for an all-new body and chassis can exceed $1 billion. In fact, the use of steel in two major industrial activities, namely, construction and automobile manufacture, has been in decline.

The global steel industry has undertaken a number of studies to demonstrate the effective use of steel in producing lightweight, structurally sound, steel automotive components that are able to be manufactured and affordable.

UltraLight Steel Auto Closure (ULSAC) Consortium[3]

- This program began as a concept development program, which produced concept designs for doors, hoods, decklids and hatches that are up to 32% lighter than benchmarked averages and ten percent lighter than best-in-class, while meeting stringent structural performance targets
- In addition to looking at body weights, the ULSAC program has set its sights on automobile closures: doors, hoods, decklids and hatchbacks.
- Closures are an easy target because they were not part of the basic structure and not part of the crash-energy management system for an automobile.
- Benchmarking used against 1997 model year vehicles
    - The benchmark vehicles were chosen to provide evaluations of specific closures. For the door these included roof integrated, frame integrated and frameless. Hood design concepts included conventional and grill integrated. The decklid design was the conventional with a tail, and the hatch design was the lift gate type
- In May 2000, the ULSAC Consortium released the Validation Phase results for a complete frameless door structure. The door structure featured a high and ultra high strength steel tubular

frame and a stamped outer panel of 0.7 mm 260 steel. The complete door structure weighed 10.47 kg (normalized mass, 13.27 kg/m2). This is 22 % lighter than the framed door best-in-class benchmark and 42 percent lighter than the average frameless door used as a Validation Phase benchmark. This was achieved without compromising safety or structural performance and at no cost penalty.

  - The ULSAC frameless door with stamped outer panel weighs just 10.47 kg. This is 1.76 kg below the target mass of 12.23 kg
  - ULSAC door achieved 33 % mass savings over the average benchmark from a wide range of door structures
  - The ULSAC DH door structure featuring a 0.7 mm thickness Stamped Panel Front Door Outer was measured at a mass of 10.47 kg. This is 1.76 kg below the target mass of 12.23 kg as specified in the ULSAC Concept Phase

- The normalized mass value of ULSAC DH door structure at 13.27 kg/m2 is significantly below the target of 15.50 kg/m2 and well into the target range. Compared to the benchmarking range stretching from 19.74 kg/m2 to 23.02 kg/m2, the ULSAC door structure shows a reduction in normalized mass in the range of 30% to 42%.

UltraLight Steel Auto Body Program (ULSAB)[4]

- Intent of this program is to reduce the weight of steel auto body structures while maintaining their performance and affordability.
- High strength steels (HSS) represent a new frontier in automotive design and manufacturing. The properties of the steel allow thinner gauges to be applied throughout an auto body, rendering a stronger, lighter vehicle without significant changes in cost structure.
- ULSAB structure showcases a lightweight manufacturing option for the auto industry, with weight savings up to 36% against benchmarked vehicles. But the weight reduction doesn't come with a cost or a performance penalty.
- Report entitled: the *UltraLight Steel Auto Body Final Report.*

Since the report introduction in 1998, there are a number of current vehicles using high amounts of high strength steel including:

- The 1999 BMW 3-series has a body structure weighing 230 kg with a high strength steel content of 50 percent. The previous model car contained less than 5 percent.
- Ford's new Focus uses high strength steel for both the body structure and exterior body panels.
- The new Mercedes Benz S-Class uses 38 percent high strength steel, which contributes to lower body weight, an increase in torsional stiffness of 70 % and improved crash performance.
- Toyota's latest sub-compact car, Vitz, uses high-strength steel in 48 % of the mass of its 253-kg body-in-white, which weighs 17 kg less than its predecessor, the Starlet.
- Ford's Windstar utilizes almost 60 % high strength steel

ULSAB-AVC (Advanced Vehicle Concepts)[5]

- AVC is a design initiative the steel industry to show that steel can be the most efficient, environmentally optimal and affordable material for future generations of vehicles
- ULSAB-AVC has matched a number of its parameters to the goals of the now defunct Partnership for a New Generation of Vehicles (PNGV) program
- The ULSAB-AVC design for a PNGV-size vehicle aims to come in between 2,276 lbs. (1034 kg) and 2,375 lbs. (1077 kg), depending on the engine selection. That's less than the two cars Ford and GM recently rolled out for PNGV. The Ford Prodigy weighs in at 2,387 lbs. (1083 kg) and GM's Precept: 2,587 lbs. (1173 kg).

- AVC is taking a holistic approach to the development of a new, advanced steel automotive vehicle architecture. The scope of the program is intended to go beyond the body-in-white to include closures, suspensions, engine cradle and all structural and safety relevant components.

UltraLight Steel Auto Suspensions[6]

- Project objectives are to reduce the mass of a new steel suspension by at least 20 percent versus benchmarked conventional steel-intensive designs
- Benchmarking was based on 2 types of vehicles, a Ford C class and a Pugeot 900kg vehicle
- In contrast to ULSAB, where a key focus was to demonstrate the *manufacturing feasibility* of high strength steel, the ULSAB-AVC is a concept program.

**Aluminum**

There is also competition from the aluminum industry for a material switch to aluminum, especially for use in automobiles. A significant dematerialization trend for automobiles has also come about by virtue of the use of lightweight, high-strength alloys, and synthetics as substitutes for steel and cast iron. The trend is especially evident in the automobile industry where large weight and size reductions were achieved by materials substitutions in the 1970s in order to conserve energy.[7]

One pound of aluminum typically replaces two pounds of conventional metals, resulting in dramatic weight savings without compromising safety.[8] Aluminum has one-third the density of steel. This means a component of aluminum can be almost one-and-a-half times thicker than steel while remaining 50 % lighter, when both components are designed to handle an equal load. As modern example, the aluminum-bodied Honda Insight was designed from the ground up to achieve significant fuel economy and ultra low emissions.

Partnering with the aluminum industry, automakers have made numerous aluminum-structured concept vehicles (*e.g.*, Chrysler Neon Lite and Intrepid ESX, Ford Taurus AIV, Synergy 2010, and P2000) and low-volume production cars (*e.g.*, GM EV1, Plymouth Prowler, Acura NSX, Audi) to work out cost and safety issues, create new forming, bonding, coating, and other key technologies to solve automakers' basic manufacturing problems, and get automakers familiar and comfortable with the material.

Aluminum Association Auto and Light Truck Group[9]

- This association promotes pre-competitive research programs and actions to help accelerate the use of aluminum in cars and trucks.
- The Auto Aluminum Alliance, a pre-competitive partnership among DaimlerChrysler, Ford Motor Company, General Motors and the aluminum industry, is working to find ways to further accelerate the use of automotive aluminum.
- Presently, while Chrysler is the only US company actively pursuing a broad scale application of aluminum in automobiles, there are some study results for automotive use gathered from the aluminum industry: [10]
    - Ford's research resulting from the production of 40 aluminum-intensive 1994 Sables showed an overall vehicle weight reduction of 688 pounds compared to a standard production model.
    - Vehicle weight reduction can be a very powerful technique for improving fuel economy as well - each 10 % reduction in weight improves the fuel economy of a new vehicle design by approximately eight percent
    - An argument of secondary savings result from the ability to make ancillary components smaller and lighter because they are carrying lighter loads.
    - Audi, in their development of the all-aluminum A8 sedan, found primary and secondary weight-savings compared to a similar steel vehicle to be approximately 1,100 pounds.

- Chevrolet engineers selected a new engine cradle design using aluminum extrusions for its redesigned 1999 Monte Carlo and all-new Impala cars for 2000. GM engineers considered conventional steel as well as hydroformed steel cradles for both new cars, but decided on aluminum because of a weight-savings of more than one-third.
- Ferrari designed its latest Pinifarina-penned GT, the 360 Modena, with extensive use of aluminum for the body and spaceframe, as well as several other components. The reason? According to Ferrari, the specific weight of aluminum is one third that of steel, and the weight of the overall chassis was cut by 28%, in spite of a 10% increase in volume and boosting rigidity by 40%.

However, there are offsets when doing a lifecycle analysis of aluminum versus steel

- According to research by the Massachusetts Institute of Technology (MIT), when compared to the latest steel technologies, it would take more than two decades of aluminum-intensive vehicles to try to offset the amount of ($CO_2$) put into the atmosphere by the production of the aluminum needed to build those vehicles.[11]
  - Paper entitled: "*Methods for Comparing Product Life Cycles Under Temporally Distributed Production Scenarios*".
- The study, conducted by MIT's Material Systems Laboratory, examines the comprehensive environmental impact of CO2 emissions and other polluting substances resulting from the production and use of various automotive, manufacturing materials, including aluminum, steel and composites.

Other Automotive Materials Substitutions [12]

- The Audi A12, a concept high efficiency car, uses an aluminum body and a transparent plastic roof to create an extremely lightweight vehicle. The car weighs only 1,786 pounds (810 kilograms) - about 550 pounds (250 kilograms) less than if it had been built with a conventional steel body. Yet the car is reported to perform well in strength and crash tests.
- The use of natural fiber composite panels reduces the molding time of 3-D parts, lower production emissions of toxic volatile organic compounds, and reduce vehicle weight
  - Kafus Bio-Composites is creating automobile components like door panels and trunk liners from kenaf fibers.
    - Kenaf is a fiber crop related to cotton and okra. Kafus natural fiber composites are designed as an alternative to traditional composite materials such as fiberglass reinforced plastics.
    - Marketed as Flexform mats and panels, Kafus' bio-composites can be recovered, reused and recycled.
  - Industrial hemp is being blended with resins and other synthetic fibers to make lightweight automotive parts. At the 1998 Detroit Auto Show, an Ontario company, Kenex, showed how the hemp it grows can be made into door panels and headliners, sound and thermal insulators, composite moldings, interior panels, matting, floor coverings, and truck liners.
- Composites: more and more car companies are considering the use of composites in semi-structural applications. If manufacturing costs can be reduced, composites offer the ability for lighter weight vehicles with fewer corrosion problems.
  - Michigan based G&L Universal, LLC, is producing seat back panels for the model year 2000 Cadillac DeVille, by means of a new material called Thermal Plastic Composite (TPC). The panels are the first such automotive components for the North American automotive market based on TPC, a blend of polypropylene plastic and recycled wood fiber.[13]

- Ford Motor Company wanted to shave cost and weight from its new Lincoln Navigator sport utility, so the company chose Sheet Molding Composite (SMC) for the hood. SMC hoods save approximately 10-40% in total program cost compared to steel and aluminum respectively, for vehicles with volumes of 50,000 units/year, while achieving a 25% weight savings compared to steel.[14]
- However, while lighter cars burn less gasoline, steel is easy to recycle, whereas the composite plastics that have replaced it resist recycling. Thus fuel consumption declines, but there may be an overall increase in amount of permanent waste produced and resources consumed.

## Dematerialization and Information Technology

The semiconductor industry could be considered to be the heart of the electronic supply chain. According to the so-called Moore's law, digital electronics dematerialize by a factor of 4 every 3 years. As such, developments in energy efficiency and product range can bring major improvements to final products, through, for example, low-power design and energy control devices. The electronics industry also has to address the environmental impacts of its own operations, for example, by reducing the use of chemicals and hazardous substances, waste minimization (e.g. wastewater sludge, plastics and silicon scraps), and energy efficiency. Recent efforts in electronic dematerialization have used light beams or tiny microscope tips to move single atoms from place to place on a surface.

The size and weight of computer chips, and products containing them - from radios and portable telephones to computers, are much less massive – and use less electric power – than their less powerful counterparts twenty or thirty years ago.

### Printed Circuit Board Manufacturing Process Changes[15]

- When manufacturers produce electronic, printed circuit boards, the plastic substrate must be prepared for later electrolytic copper plating. Manufacturers currently use highly toxic chemicals, including cyanide-based compounds, in an electroless plating process.
- Continental Circuits Corporation (CCC) has identified a replacement technology for electroless plating that eliminates the use of toxic chemicals in manufacturing circuit boards
- The direct-plating (or nonelectroless) copper process bypasses the metallizing step for the circuit board and eliminates toxic chemicals commonly used in the electroless plating system. Chemical activators make the nonconductive plastic surfaces conductive so copper can be directly plated to the substrate.
- The direct-plating process also increases productivity and product quality. Because the direct-plating process operates at room temperature, CCC no longer needs the cool-down period used in the conventional process.

### Electronics Company Case Studies

IBM [16]

***IBM Blue Gene Research project***[17]

- IBM and NNSA's Lawrence Livermore National Laboratory will jointly design a new supercomputer in the Blue Gene family. Called Blue Gene/L, the machine will be at least 15 times faster, 15 times more power efficient and consume about 50 times less space per computation than today's fastest supercomputers.

***IBM and energy efficiency***[18]

- In October of 2001, IBM announced the development of new chip design techniques to yield further power reductions. IBM believes these new techniques can lead to devices that operate on 1/10th the power of current devices.
    - While examining overall product energy consumption, IBM has been able to identify components where significant improvements can be made. For example, since 1991, the company's disk drive storage density has grown by 60% annually, reducing energy consumption by 99 percent.
    - Additionally, IBM's copper chip technology provides higher performing microprocessors that require 20% less energy to produce
    - IBM ThinkPad products, Achieved weight reduction of 0.3 lbs by using a thin wall material design approach
    - Another example is IBM's NetVista X40 all-on-one desktop PC, which integrates a 15-inch flat panel display with a full function computer, providing a system that is 75 percent

smaller than traditional desktops. The X40 not only fits into tight office spaces, it offers a 34 % reduction in overall weight and uses less plastics, metals and other materials

Intel[19]

- Intel's new 0.13-micron process technology and will be used to manufacture microprocessors on 300mm (12-inch) wafers
- The chip uses thinner, 0.13-micron circuits, needs less power and stores data when electronic items such as mobile phones and hand-held organizers
- The output of a 300mm process represents 240% more productivity in terms of the number of die (chips) per wafer. On a production-unit basis, 300mm wafers will use 40% less energy and water per chip than 200mm wafers.
- Intel said it built a flash-memory chip that's half the size of current models, as the biggest semiconductor maker shrinks the device to fit into smaller wireless products.
    - Earlier this year, Intel unveiled transistors just 20 nanometres wide. (A nanometer is about 10,000 times narrower than a human hair.) Today's Pentium 4 has 42 million transistors, each about 180 nanometres. The number of transistors in a microprocessor is expected to be in the billions within a few years.
- Intel has continued to work on its silicon-based transistor[20]
    - Intel's latest transistor is only 20 nm across, or 30 % thinner than Intel's previous record
    - What's more, the gate oxide layer separating the polysilicon gate electrode from the transistor's silicon base is only 0.8 nm thick, or less than three atomic layers deep.

***Intel process changes***

- Intel has used DFE approaches to reduce pollution per unit of each new generation of Intel products. This has resulted in more than a 50% reduction in total volatile organic compound (VOC) emissions since 1994. During the same time period the number of total production units has more than doubled.

Apple [21]

- Company has been taking steps to increase recyclability by using materials that can be easily recycled, marking materials with international recycling codes, standardizing designs and components to facilitate material use along product lines, and reducing the weight and material used in products.
- Apple is increasingly utilizing materials that are easily recycled into other products.
- Apple is reducing the weight and thus the materials utilized in its products, generating less material to be dealt with at end-of-life.
- As example, with the power Mac 7200, Weight is approximately 12% less than that of a comparable 7100 CPU. The number of motherboard layers was reduced from 6 to 4 - reducing mass by about 33 percent.
- Material savings have been made through substantial integration of parts (e.g. the larger chips in the design required less supporting components).

However, in the electronics industry, rapid dematerialization has been compensated for – even overcompensated for – by growth in the demand for computing and communication power for several years now. This dramatic dematerialization of electronics has not resulted in a corresponding reduction in material flows, as the current amount of electronics waste indicates that material throughput continues to increase. This is in part due to what is termed a *rebound effect*, a concept that refers to a potential created by efficiency gains that is balanced off or even overcompensated for by quantitative growth. To

the extent that dematerialization is accompanied by lower costs and financial savings to consumers, demand for the products tends to increase.

Many thought that information technology and the electronic information revolution would create a paperless office, paper remains the dominant and essential vehicle of modern communications. Americans now use about a kilogram of paper per day on average, twice the amount used in 1950. By one estimate, personal computers alone account for 115 billion sheets of paper per year worldwide.

This demonstrates the significance of including ecological rucksacks or hidden flows of a material. Material input (MI) is the total material and energy flow (in mass units like kg or tons) and includes not only the materials converted within the economy but also those "left aside", for example at mining sites. As hidden flows may also be harmful, this broad concept of scale is beneficial in looking at dematerialization trends. [22]

As example:

- It is by no means clear that the total mass of consumer electronic products sold each year is declining. As computer chips become smaller and more compact the manufacturing process becomes more and more complex. The ratio of indirect material consumption to material actually embodied in the product is extremely large. A chip weighing 1 gram requires processing in which several hundreds or even thousands of grams of photo resists, acids, solvents and neutralizers are used and discarded.
- The Wuppertal Institute has done a study of material intensity for the PC and have arrived at a figure of 16-19 metric tons per PC, thus:
    - 0.1% of the physical mass transformed to produce 1 PC goes into the product
    - IBM in its own assessment of the material intensity of its product has offered a value of 1.4 percent[23]

## Dematerialization and Packaging

Several individual end products manifest dematerialization. Containers, for example, have generally become lighter. At mid-century, beverage containers were predominately made of steel or glass.[24] Today, there is substantial use of aluminum and plastics, but glass bottles have also been reduced in weight; since 1980, their average weight has fallen by over 30 percent. [25]

### Aluminum Cans

Cans of aluminum, a material one-third the density of steel, entered the scene a decade later and grew from a 2 % market share in 1964 to almost 90 % of the soft-drink market and about 97 % of the beer market by 1986. The aluminum can has itself been lightened by 25 % between 1973 and 1992.

- Twenty-four years ago, one pound of aluminum made 21.75 12-ounce cans. By developing new technologies to reduce the can's weight, the industry now produces an average of 31.92 cans from every pound of aluminum.
- The weight reduction continues through the use of smaller can ends. The can manufacturing industry once used the "206" end universally, which weighs (including the tab) an average of 8.5 pounds per thousand. Today, the industry has moved towards "204" and "202" ends, which are considerably smaller and use far less material to manufacture. In fact, the "202" end weighs an average of 6.11 pounds per thousand.26

### PET - polyethylene terephthalate

General packaging trends have created lighter products and packages. In 1988 the soft drink industry used an average 453 grams of packaging in the manufacture and distribution of each liter of soft drinks. By 1998, this amount of packaging used had been reduced to only 148 grams per liter, a reduction of 67 percent.[27] Over half the reduction in packaging use is the result of substituting lightweight PET bottles and aluminum cans to replace heavier steel cans and refillable/non-refillable glass bottles previously used for packaging soft drinks. In 1976, polyethylene terephthalate (PET) resins began to occupy a significant portion of the market, especially for large containers, where glass had previously dominated. Switching from glass to lighter PET plastic for single serve containers reduced that package's weight by 90 percent.

Nestle undertook a change from PVC to PET meant a significant reduction in bottle weight, along with better transparency and resistance. For example, a 1.5 liter bottle made from PVC weighed 45 g; the same bottle made with PET weighed 37g. Today, a 1.5-liter PET bottle weighs between 28 and 33g depending on the complexity of its shape. Compared with 1996, this represents a weight reduction of 17 percent. Expressed another way, 90 grams of PVC previously produced two bottles. Now the same quantity of PET yields three bottles of equivalent capacity, which represents an overall reduction of more than 33%.[28] Industry-wide, since 1979, the weight of 2-litre plastic PET soft drink bottles has been reduced by 31 percent.

**Company packaging case studies**[29]

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| **Anheuser-Busch Companies** | ▪ Over the past 20 years, the weight of its cans has been reduced by 36% and the weight of its glass bottles has been cut by 23%<br>▪ The company also recycles one can for every can of beer filled by its 13 breweries - 17 billion - making it the largest recycler of aluminum beverage containers in the world. |
| **The Coca-Cola Company** | ▪ Reduced the amount of raw materials used to produce Minute Maid chilled, multiserve bottles through lightweighting plastic and removing the foil seal. This saved more than 1,000 tons of HDPE and 10 tons of foil.<br>▪ Coca-Cola has also looked to redesign its aluminum cans, reducing weight of these cans by nearly 6% |
| **Coors Brewing Company** | ▪ In 1993, Coors prevented the generation of 27,218 tons of glass by reducing the amount of glass necessary to make 7, 12, 32, and 40 oz. bottles. By reducing clay-coated bottle carriers by 10%, Coors avoided an additional 992 tons of waste material. |
| **DuPont** | ▪ DuPont has implemented a corporate Environmentally Improved Packaging Program to reduce packaging waste resulting from the shipment of its products to customers by at least 50% by the year 2000. |
| **Dow Chemical** [30] | ▪ A life cycle design demonstration project initiated between the U.S. Environmental Protection Agency, Dow Chemical Company, and the Center for Sustainable Systems at Michigan to investigate milk and juice packaging design.<br>▪ An objective of this project was to develop design metrics and guidelines for environmental improvement of milk and juice packaging systems. Material production energy accounted for a large portion of the total life cycle energy for these systems. Conversely, post-consumer waste was responsible for a majority of their life cycle solid waste generation.<br>▪ The one-gallon, 50-trip refillable HDPE bottle generated the least solid waste over its life cycle (4 kg/1000 gal). In contrast, the single-use, one-liter glass bottle generated the greatest mass of life cycle solid waste (1220 kg/1000 gal). |
| **McDonald's** | ▪ The company has many waste prevention efforts - One example is reducing the amount of material in Happy Meal cartons and bags, saving 379 pounds per store per year.<br>▪ The company has also reduced the sized on in store napkins, decreased the weight of carryout bags, and decreased the weight of in store trays.[31]<br>▪ The company also has Coca-Cola drink syrup is now delivered in reusable, refillable containers instead of cardboard containers, cutting millions of pounds of packaging off McDonald's annual waste. |
| **Allergan, Inc.** | ▪ Company has redesigned packaging to eliminate more than 950 tons of boxboard and plastic.<br>▪ Eliminated more than 187 tons of PVC by redesigning lens packaging, saving $1.5 million. |

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| **Stonyfield Farm** | ▪ Stonyfield selected lightweight plastic for its yogurt containers after examining the lifecycle environmental impacts of alternative containers.<br>▪ After examining its options (including glass, poly-coated paper, and plastic), company chose a lightweight plastic. Glass, which is widely recycled and made from recycled material, was rejected as the environmental costs of transporting the heavy material outweigh the benefits. The energy (fossil fuels) used over the entire life of the glass package for its manufacture and transport exceeds the energy that goes into the manufacturing and transporting of a plastic container.<br>▪ Their quart containers are over 30 percent lighter today than they were just 10 years ago. By using polypropylene instead of HDPE, in 1998, Stonyfield Farm reports preventing the manufacture and disposal of over 85 tons of plastic.<br>▪ In developing their yogurt 6-packs, the company used a thin plastic seal vs. a lid on each cup, and avoided the use of energy-intensive aluminum seals that are common.<br>▪ University of Michigan's Center for Sustainable Systems undertook a life cycle assessment was conducted to evaluate the total environmental burdens of the yogurt product delivery system (PDS) for Stonyfield Farm. [32]<br>▪ Research determined that the total energy consumption for the current 2, 4, 6, 8 and 32 oz. containers were 3800, 4080, 4760, 4020, and 2930 MJ per functional unit, respectively. The 32 oz. containers consumed 27% less energy than the 8 oz. containers, and if all Stonyfield yogurt were sold in 32 oz. containers, the annualized energy savings would be equivalent to 11,250 barrels of oil. |
| **Johnson Wax** | ▪ According to company reporting, package redesign and light-weighting for "Lemon Pledge" and "Shout" reduced material use by 974,000 pounds for an annual cost savings of $423,000 |
| **Intel** [33] | ▪ Intel's Logistics Transport Materials Engineering (LTME) Team implemented a packaging design change for CPU shipping trays. The design optimized the number of CPU's in a box, replaced plastic foam cushioning with a 100% paper material and introduced an industry breakthrough by replacing the expensive standard tray cap with a lighter weight solution. The redesign is projected to save more than 800,000 lbs of plastics over the next 3.5 years.<br>▪ Intel's SMG Packaging Engineering team implemented a package design change for network interface cards. The change included reducing the size of the protective clamshell by nearly 1/3 and using a thinner gauge material. As a result, the smaller clamshell is 45% lighter. This redesign is saving an estimated 320,000 lbs of plastic annually.<br>▪ In addition, the smaller clamshells allowed the SMG Packaging team to reduce the size of the bulk shipping carton by 40%. The new carton is 52% lighter. This is saving an estimated 270,000 lbs of corrugated packaging annually. Because of the smaller, lighter, package design, less space is used to ship more product. This also results in a reduction of energy and resources used in transporting these products |

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| | to our customers. |
| **Digital (Compaq)** | ▪ Compact Disc ROM packaging reduction of 88%.<br>▪ Computer cabinet packaging reduction of 31%, with the use of foam almost eliminated. |
| **UPS** [34] | ▪ Redesigned the flaps of its basic Express box, reducing the amount of material by 9%. In addition, UPS has achieved additional lightweighting of the box by reducing the total weight and fiber amounts. |
| **Baxter** | ▪ Reduced the weight of 5- and 10-liter containers approximately 15 percent<br>▪ Decrease the weight of amino acid product leaflets 25 percent<br>▪ Since 1990, we have cut packaging 27 percent with the weight of one of our major IV product lines being reduced 16 percent. |
| **Procter & Gamble** [35] | ▪ P&G redesigned its diapers to use substantially fewer raw materials and weigh about 30 percent less than previous diapers, thereby using less packaging and requiring fewer trucks to distribute.<br>▪ By introducing a single bottle design for several of its hair and personal care products, the company was able to reduce the bottle raw material use by 9 to 22 percent and improve manufacturing efficiency over 30 percent<br>▪ By redesigning plastic bottles used for vegetable oils, P&G cut their use of plastic by 1,250 tons. |

## General Company Dematerialization Case Studies

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| **Ericsson** [36] | ▪ Ericsson has worked to reduce the material intensity of many of its products.<br>▪ The radio base system transmits and receives communications over the air to and from mobile phones, providing service over a defined geographic area. By utilizing microelectronics, Ericsson has used 33% few resources and generated 33% less waste in developing this product.<br>▪ Using a DfE approach the company has been able to achieve a 50 to 70 % increase in capacity with half the materials and energy use of the previous generation of products.<br>▪ Today's Ericsson cell phone is barely one-third the weight of the company's phones launched in the early 1990s. |
| **Canon** [37] | ▪ Reduced the size and weight of its cameras and videos<br>▪ Installed power saving feature in laser beam printers, facsimile machines, and Bubble Jet printers.<br>▪ Canon started a project in 1991 to develop lead-free glass.<br>▪ Canon also works to reduce glass waste by making lenses of smaller diameters and using technologies to shape and process glass more effectively.<br>▪ Canon is making cameras more compact and lighter in weight to help conserve resources.<br>▪ Canon was also the first in the world to introduce the new concept of using diffractive optical element for camera lenses in 2000. By making the diffractive optical element multi- layered, Canon was able to utilize the merits of the diffractive optical element and succeeded in producing a prototype of the EF 400mm F4 DO IS USM lenses. Compared to the conventional lenses, the new lens is much more compact, using less material. |
| **Novo Nordisk** [38] | ▪ This pharmaceutical company participates in the industrial symbiosis at Kalundborg, Denmark and has also demonstrated the competitive advantage of developing biologically based industrial materials such as industrial enzymes.<br>▪ Enzymes are natural catalysts that speed up chemical reactions without being consumed in the process. They are biodegradable. They function best in mild conditions so their use requires up to a third less energy than many synthetic chemicals need. They are used in detergent, fabric, food processing, pulp and paper, leather, industrial cleaning, and agricultural applications. |
| **Bristol-Myers** [39] | ▪ Bristol-Myers has instituted a "Process Greenness Scorecard" that looks to reduce or eliminate hazardous chemicals in all bulk pharmaceutical syntheses. |
| **Electrolux** [40] | ▪ Electrolux uses sustainability as a driver for new product design. As a result, the company makes among the most efficient appliances in the world.<br>▪ The company is not concerned about, nor do they resist, energy efficiency standards because they know they will meet or exceed any standards set for their industry. In fact, energy efficiency standards work to their advantage because they are |

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| | better positioned to meet these appliance standards than their competitors. |
| **Interface** | ▪ Interface has conceived a new way to make money from carpet: by leasing carpet service. Now the company offers perennial carpet leasing plans, where his firm can restore carpet continuously, replacing only the worn sections.<br>▪ Thanks to QUEST, the company has saved over $20 million by such activities as producing post-industrial recycled nylon carpet, improving the efficiency of turnover for beams of yarn by 25%, reducing hexane solvent usage by 16% with the implementation of a new carpet drying procedure, and reducing scrap yarn from beams at one of their manufacturing sites by 75%.<br>▪ Carpets made with Solenium last four times longer than normal carpets and require 40% less material; in other words, Solenium has enabled Interface to reduce materials intensity in its carpets by more than 85%.<br>▪ For the first time this material is completely recyclable into identical product with no downcycling.<br>▪ Carpet tiles that Interface produces could be a more ecologically sound alternative to typical carpets because worn tiles can be replaced rather than replacing the entire carpet. |
| **Herman Miller** | ▪ Rugged, reusable plastic bins, rather than disposable packaging, are used to ship materials from vendors and between factories. Returnable packaging has also yielded other benefits, including less damage to shipped goods and increased efficiency and productivity in the manufacturing areas.<br>▪ For some time now, powder coat finishes have been used on metal parts with great success. Powder coat finishes on wood, however, are new. At Herman Miller, the process is being used on fiber board components featuring soft, rounded edges. |
| **Steelcase** | ▪ Steelcase reduces packaging waste outside its operations by shipping products uncartoned where possible, reusing containers, and lowering the board grade of those cartons still used. Pallet reuse reduces waste generation at Steelcase by 296 tons per year, and yields $23,130 annually in pallet sales and avoided disposal costs. [41] |
| **Nike** [42] | ▪ In terms of packaging, in 1996 Nike reduced its 18 shoe box designs to 2 basic designs. Furthering this effort, in May 1998 Nike changed the designs and manufacturing again, reducing material usage by an additional 10%.<br>▪ In China and Indonesia, Nike has reduced solid waste generated per pair of shoe produced by 29% (as of 2000).<br>▪ Using a PGI Miratec construction method to make some apparel, this reduces weaving energy use by over 40%, and the fabric requires no dyeing or finishing, reducing that impactful process as well.<br>▪ EVA foam sandal – manufactured in a single material |

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| | process, has little waste and eliminates the use of secondary components. |
| **Sony** [43] | ▪ By adopting substitutes and alternative processes, the company plans to reduce the environmental impacts of its products.<br>▪ Walkman boasts the world's smallest size, lightest weight and longest playback time of 100 hours.<br>▪ The Eco TV is halogen-free, eliminates hazardous materials, uses less total material to produce, is 99 % recyclable, and is designed for easy disassembly.<br>▪ In the area of printed circuit board (PCB) technology, the product requirements meant the use of the very latest surface mount technology. Subsequent versions of the TR5 reduced the PCB size by 75%. This enables the company to manufacture high-density component packages and equipment. |
| **Xerox** [44] | ▪ Over 72,000 tons of old machines made by Xerox were recycled or refurbished by the company in 1998. This program has made it possible for Xerox to drastically cut its use of virgin materials in new machines.<br>▪ By building the concepts of easy disassembly, durability, reuse and recycling into product design, Xerox works to maximize the end-of-life potential of products and components. Today 90 percent of Xerox-designed equipment is remanufacturable. |
| **Carrier** [45] | ▪ By material substitution, and process modification, Carrier successfully reduced its purchases of chromium and discontinued its use of barium entirely.<br>▪ Carrier, the world's largest manufacturer of air-conditioners, is experimenting with leases of comfort instead of sales of air-conditioners. Making the equipment more efficient or more durable could give Carrier greater profits and its customers better comfort at lower cost.<br>▪ Carrier's new line of Ecologic™ chillers offer higher operating efficiencies, lower sound levels and smaller footprints than previous models.<br>▪ The Ecologic chillers meet four of the six environmental performance parameters Carrier established in 1993. The parameters are: refrigerant, efficiency, quiet operation and product size and material reduction.<br>▪ A 175-ton water-cooled chiller fits though a three-foot doorway and is up to 30 percent lighter than similar units, making it ideal for replacement applications," he added. The 30GX air-cooled chiller is up to 50 percent smaller than the units it will replace, simplifying installation and providing more cooling in a given space. |

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| **Gillette** | ▪ Gillette reduced the water used to make razor blades by 97%, and that used to make pens by 90 percent. |
| **Astro Power** [46] | ▪ AstroPower develops, manufactures, markets and sells photovoltaic solar cells, modules, and panels for generating solar electric power.<br>▪ AstroPower's superior manufacturing capabilities feature proprietary Silicon-Film™ production equipment and the use of recycled semiconductor wafers as raw materials.<br>Waste is prevented both by efficient material usage and manufacturing techniques. |
| **NRELs** Photovoltaic Manufacturing Technology Project [47] | ▪ Helps the PV industry explores new manufacturing options and ideas for improved PV modules.<br>▪ Siemens Solar has implemented production of the 150-mm cell and module product line, which leverages the use of silicon by over 30% in the production of solar cells; continued to improve manufacturing productivity and yield by over 10 percent. |
| **HP** [48] | ▪ Efforts have been made by HP to use fewer raw materials by reducing the number of parts needed to manufacture the Vectra PC and DeskJet printers. The PC now requires 350 parts as opposed to 1,650, and the printer is 35% lighter due to the reductions. |
| **Intel** | ▪ In 1999, Intel introduced its Instantly Available Personal Computer (IAPC) technology, allowing PCs to run more efficiently while reducing their energy use by up to 60%. |
| **Automotive Powder Paint Systems** [49] | ▪ U.S. automobile manufacturers are seeking better paint application systems to replace liquid paint-spray systems.<br>▪ Chrysler, as a member of the U.S. Council for Automotive Research, is working with the Low Emission Powder Consortium to develop powder coatings that could eventually replace liquid-paint-spray systems in auto manufacturing.<br>▪ The powder-paint system is an extremely efficient method for applying coatings to vehicles. With the powder-paint system, because the overspray can be captured and recycled, 95% of the paint solids are deposited on the vehicle surface. In comparison, only 43% of the solids are deposited by the paint-spray system. Thus, each paint-spray booth creates a waste stream of 600 tons (544 tonnes) of solid waste/yr that must be landfilled. |

## Servicizing and Dematerialization

Servicizing is the transformation from product to service-based enterprises, in which suppliers deliver function as the source of added value, rather than the shape or form of a specific product. Servicizing is fast becoming a major force in how firms manage material input, throughput and output. The idea is gaining a key position in sustainable economic policy and environmental business strategy.[50] An idea is that if a traditional computer manufacturer started leasing "computer services", this would change the design requirements for their products and might well force them to consider full life-cycle costs resulting in modular designs. Two brief company examples are Xerox moving from a photocopy machine maker to the "Document Company" and IBM from a mainframe and PC maker to an information services company.

**Industry Trends in Servicizing**[51]

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| **Castrol Inc** | ▪ Castrol is a supplier of professional lubricants and associated services. They offer lubricant service packages that provide the customer with more than just the product. These include needs assessment, site surveys, analyzing costs and productivity indicators, training, and performance assessment for opportunities in reducing lubricant consumption. They develop profit from cost savings given to customer, rather than just the volume of chemicals they sell. |
| **DuPont, USA** | ▪ DuPont manufactures carpets and fibers. It has introduced a product-service solution by leasing carpets to consumers. It also offers a service package for maintenance and carpet cleaning.<br>▪ DuPont is working with Ford UK in its painting operations. Compensation would be on a per-car basis instead of on the basis of per gallon of paint sold. Effectively, this move transforms DuPont from a paint supplier to a provider of car painting services. |
| **Electrolux, Sweden** | ▪ Called Pay-per-Wash, used on the Gotland Island in Sweden. The island was chosen because it was the only place in the world at that time with intelligent electrical meters installed in 7000 households, which allows for remote reading. The pilot was introduced into 50 households on the island. Instead of charging customers to buy a washing machine, the customer borrows a new washing machine for and pays SEK 495 as a fee to Electrolux that covers the cost of installation. In return customers are provided with Electrolux's 'intelligent' energy efficient washing machine. Customers pay for the function of washing alone. |
| **Carrier** | ▪ The air-conditioning systems manufacturer is moving toward leasing comfort rather than selling air conditioners. With this type of leasing service, Carrier gets paid to provide a certain level of comfort to its customers, and can achieve higher profits by making its equipment more durable and efficient than its competitors. |
| **Interface Carpets** | ▪ Interface offers an "Evergreen Service Contract" whereby customers lease floor-covering services as opposed to purchasing carpet. After all, they only want to walk on and look at the carpet, not actually own it. For a monthly fee, customers pay Interface for the maintenance of the carpeting. The incentive to increase the product's durability therefore transfers from the customer back to Interface. By utilizing a system of interlocking tiles, Interface rotates and then replaces only the 20% of the carpet tiles that actually show 80% of the wear. |

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| **Herman Miller (Coro)** | ▪ As a service business, Coro manufactures no products. Rather, it services customers who have purchased furniture products from Herman Miller and other manufacturers. Herman Miller's national dealer network carries out the actual movements of furniture and office contents.<br>▪ Coro provides large corporate buyers with move and reorganization services. |

While dematerialization is frequently applied to consumer end products and production processes, it could be equally applicable in non-manufacturing fields such as agriculture. Reduction of pesticide use per unit crop, for example, dematerializes food production. It is also worth recognizing that the similar concept of producing equal units of energy while releasing less carbon as a result of fossil fuel combustion, commonly referred to as "decarbonization" is increasingly considered an important sub-class of dematerialization

## Agriculture and Dematerialization

**Wood production** [52]

- The amount of wood used to make each ton of industrial wood products has decreased by 23% from 1945 to 1990
- The total amount of wood used in the US has grown by only 63% since 1900, despite a tripling of the population.

**Integrated Pest Management** [53]

- IPM strategies focus on scouting for pests and reducing pesticide use. Integrated Crop Management techniques combine those practices with improved fertilizer management and farming methods.
    - Using Arizona Extension IPM methods, cotton farmers reduced insecticide spraying in 1999 to the lowest levels in 20 years
    - Pesticide applications on apples dropped by 33 to 50 %, thanks to Vermont Extension IPM efforts.
    - In Accomack County, Virginia, less than 1 % of the soybean crop was sprayed for corn earworm in 1999, thanks to Virginia Tech Extension's IPM field scouting. Just 26 % of the state's soybean acreage was treated with insecticide in 1999, compared with 40 % in 1995.
    - Connecticut IPM full-season training programs for sweet corn, field corn, peppers, squash, tomatoes, turfgrass, bedding plants and poinsettias have reduced annual pesticide use by nearly 14 tons on 1,270 acres. This is a 43 % reduction in pesticide use by the 77 IPM program participants.

## Decarbonization

Decarbonization could be defined as an evolution of the energy system for more service while burning less carbon, through more low-carbon fuel (natural gas) or no-carbon fuel (hydrogen) and through more efficient generation, distribution and use, but is also applicable to changes in the energy intensity of manufacturing and production – a reduction in carbon emissions per unit of output.

The Federal Energy Information Administration has reported that emissions of carbon dioxide by the United States had increased by an average of 1.37 % a year in the 1990's -- only about half the 2.6-percent rate of growth in economic production. Some analysts say the discrepancy is evidence that the economy is being decoupled from carbon.

**Energy Intensity**

- In the past, energy minimization has not ranked as a central consideration of industrial process designers. It is now becoming more so, as global warming concerns and energy taxes begin to enter policy discussions. The relative efficiency of energy use is measured by a parameter termed the industrial energy intensity, expressed in energy units per monetary unit of value added. The recent trend is toward decreasing energy intensity, with decreases of about a factor of 3 occurring over the last 30 years in a number of countries. [54]
- In the immediate pre-Internet era (1992-1996), GDP growth averaged 3.2 percent a year, while total energy demand grew 2.4 % a year. In the Internet era (1996-2000), GDP growth is averaging more than 4 % a year, while energy demand is growing only 1 % a year.
- The design of industrial equipment and the ways in which industry extracts and processes resources play major roles in the rate of energy use. This, in turn, affects the rate at which humans generate carbon dioxide and other potential global climate-change gases. Devices that reduce power consumption, processes that operate more efficiently, and resource provisioning that minimizes energy consumption are all important in continuing to change the historical pattern. [55]

**Case Studies[56]**

- DuPont's 1,450-acre Chambers Works in New Jersey, which reduced energy use per pound of product by one-third, and cut global warming pollution per pound of product by nearly half
- An Arkansas steel tube manufacturer that replaced a key electric motor and drive with a new, high-efficiency system. The 34 % energy savings would have paid for the new system in five years, but the new setup also reduced the steps in the production process
- A South Carolina aluminum refiner that analyzed its dust collection system and found that a few modest operational changes would reduce energy consumption 12 % a year, and reduce carbon dioxide emissions by over 2,500 tons a year with no capital outlay whatsoever
- Semiconductor suppliers, STMicroelectronics has also put together a design for a next generation fabrication plant that reduces carbon dioxide emissions per chip by 75 % compared to their average plant, at a lower initial cost.

## Life-Cycle Analysis (LCA) and Dematerialization

The U.S. economy is among the most material intensive economies in the world, extracting more than 10 tons (20,000 lb) of "active" material per person from U.S. territories each year. Most of this material becomes waste relatively quickly. By one estimate, only 6 % of this active material is embodied in durable goods; the other 94 % is converted into waste within a few months of being extracted.[57]

LCA emphasizes identifying and reducing the overall impact the product has upon the environment, from extraction of material, through production, to disposal. "An inventory phase analyzes system inputs of energy and materials along with outputs of emissions and wastes throughout the lifecycle

One item that is clear is that the ability to understand the systemic effects of different materials in different applications is primitive at best. Indeed, even now many life cycle assessments consider only one material in one application, and the substitution and systemic effects are frequently overlooked. [58] However, a number of companies have utilized LCA in assessing some of their products and processes:

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| **Ericsson** | ▪ Ericsson has explored the use of LCA in order to have an assessment tool that can help Ericsson to prioritize the most significant environmental impacts of its business activities. |
| **Electrolux** | ▪ The company has used LCA to demonstrate how use of the appliance accounts for about 90% of its environmental impact, thus enabling the company to focus on energy efficiency and design for reuse. |
| **Mercedes** | ▪ Analysis (LCA) of S-class car.<br>▪ A comparison with its predecessor spanning the full life cycle of a Mercedes-Benz S-Class car (production, service life covering 300,000 km, and end-of-life disposal) reveals the following: Owing to the use of lightweight materials, more energy is required to build the new S-Class than its predecessor. However, over its full life-cycle, the new S-Class will require far less primary energy – in fact the energy savings alone amount to more than it takes to build a new S-Class sedan. When the vehicle has covered just 25,000 kilometers it will already have made up for the extra amount of energy required in its production. |
| **Volvo** | ▪ The design of components and the choice of materials during product development are important factors in LCA. Aspects such as energy and water consumption, emissions to air, chemicals usage, and the management of waste and residual products are considered in the context of production. In the recycling area, assessment is made of the materials specification and design aspects of product development to ensure simpler recycling or safer disposal 20 years down the line. |
| **Apple** | ▪ Not undertaking scientific LCAs, but Apple has looked to review key product attributes that its design teams could influence – material reductions, modular design, design for recycling. |

Dematerialization at its most basic unit is the reduction of material use per unit quality of life. It is also increasingly a byproduct of the evolution of a "functional economy" where consumers purchase function, rather than physical product, from service providers. In such cases, it may be necessary to understand when dematerialization is and is not appropriate. [59]

Nevertheless, there are a number of factors that run counter to dematerialization, and with which companies pursuing a gamut of approaches to reduce their material intensity – from DfE, pollution prevention, and input-output analyses, to life-cycle assessments and industrial ecology - need to be concerned. The primary factor is product quality. Improvements in product quality generally lead to enhanced dematerialization, but if product quality is poor, although individual product mass may be lower, products are likely to be discarded sooner, so that less is not necessarily less from an environmental point of view. If smaller and lighter products are also inferior in quality, then more units would need to be produced, and the net result could be a greater amount of waste generated in both production and consumption. From an environmental viewpoint, therefore, dematerialization could perhaps be effectively defined as the change in the amount of waste generated per unit of industrial product.

## Dematerialization and Nanotechnology

Nature applies nanotechnology daily to grow the multifunctional cells and tissues of plants and animals from a single biological cell, which contains programmable sequences of molecules. Nanotechnology already exists in its "untamed" natural form, and it already helps run our daily economy—for example, when we use quantum-based lasers to read compact discs and compact videodiscs. For example, carbon nanotubes and nanoparticles are commercially available for the manufacture of specialty products such as antistatic compounds and transparent coatings. Today, nanotechnology is still in its infancy, and only rudimentary nanostructures can be created with some control.

However, commercial nanotechnology products are already available and include for instance new semi-conductor lasers and computer hard disk drives based on giant magneto-resistance. In the last several years, multibillion-dollar markets based on nanotechnology have been developed. For example, in the United States, IBM has developed magnetic sensors for hard disk heads; Eastman Kodak and 3M have produced nanostructured thin-film technologies; Mobil has synthesized nanostructured catalysts for chemical plants, and Merck has produced nanoparticle medicines. Toyota has fabricated nanoparticle reinforced polymeric materials for cars in Japan, and Samsung Electronics is working on a flat-panel display with carbon nanotubes in Korea. [60] Novel materials are being marketed, such as for spectacles with scratch-resistant nano-coatings or sunburn lotions containing ultraviolet-absorbing nanoparticles. [61]

### U.S. National Nanotechnology Initiative

The Federal government has initiated the National Nanotechnology Initiative (NNI), which will provide almost $520 million in funding in fiscal year 2002. The NNI is a multi-agency effort within the federal Government that supports a broad program of Federal nanoscale research in materials, physics, chemistry, and biology. The NNI will accelerate the pace of fundamental research in nanoscale science and engineering, creating the knowledge needed to enable technological innovation, training the workforce needed to exploit that knowledge, and providing the manufacturing science base needed for future commercial production. The initiative will support long-term nanoscale research and development leading to potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, environment and energy, chemical and pharmaceutical industries, biotechnology and agriculture, and computation and information technology. As part of this nanotech initiative, NSF is now funding six new applications-oriented nanotech research centers[62]

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| Center For Integrated Nanopatterning And Detection Technologies | Northwestern University | Chemical and biological sensors | |
| Center for Nanoscale Systems in Information Technology | Cornell University | Electronics, information storage and communications | |
| Center for the Science of Nanoscale Systems and Their Device Applications | Harvard University | Electronic and magnetic devices and quantum information processing | |
| Center for Electronic Transport in Molecular Nanostructures | Columbia University | Materials for electronics, photonics and biology | |
| Center for Biological and Environmental Nanotechnology | Rice University | Materials for environmental engineering and medicine | |
| Center for Directed Assembly of Nanostructures | Rensselaer Polytechnic Institute | Composites, drug delivery devices and sensors | |

**Materials and Manufacturing**

The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions has the potential to revolutionize segments of the manufacturing industry.

Applications include (a) manufacturing of nanostructured metals, ceramics and polymers at exact shapes without machining; (b) improved printing brought about by nanometer-scale particles that have the best properties of both dyes and pigments; (c) nanoscale cemented and plated carbides and nanocoatings for cutting tools, electronic, chemical, and structural applications; (d) new standards for measurements at nanoscale, and (d) nanofabrication on a chip with high levels of complexity and functionality.

Buckyballs [63]

- Buckyballs are named for the architect/engineer R. Buckminister Fuller, the designer of the geodesic dome. Infinitesimal soccer ball-shaped clumps of 60 carbon atoms, they could be used to make everything from plastics to batteries
- A Buckytube may be the strongest substance that will ever exist, with a tensile strength one hundred times greater than steel, but only one-sixth the weight of steel. It is a highly efficient conductor of electricity, comparable to copper or silicon, has excellent thermal conductivity, and has the size and perfection of DNA. Buckytubes have the potential to revolutionize polymers, electronics, medicine and many other industries. [64]
- Buckballs are 100 times stronger than steel, yet six times lighter
- Carbon nanostructures, such as the 60-molecule spheres known as buckyballs, have found wide technological uses, but undesirable electronic and mechanical properties have limited their applications.

Nanotubes [65]

- Nanotubes, once considered the waste material that sat at the bottom of chambers used for making bucky balls, are being looked at with newfound respect by physicists, electrical engineers, and computer and materials scientists
- A carbon nanotube is a graphite sheet rolled into a tube, approximately 1.1 nanometers (nm) across, capped at each end by half a C60 molecule. This arrangement of carbon gives nanotubes certain unique properties. For their diameter, they are 6 times lighter and 10 times stronger than steel1 along their length. They can also carry around 100 times the electrical current of steel
- The tube is formed when two ends of graphite join together--like chicken wire around a post--and half a buckyball attaches at each end
- The field-emitting characteristics of carbon-nanotube films have attracted serious interest from the giants of the display industry. Samsung, for example, plans to market a flat-panel color display using nanotubes
    - Research at IBM indicates that nanotubes transistors should be competitive with state-of-the-art silicon devices. Nanotubes could also be used to store hydrogen to power electric vehicles

General Motors [66]

- General Motors (GM) recently revealed that it is using one of the first of these true nanomaterials-a novel polypropylene (PP) composite produced by Basell-in a low-volume part for several of its 2002 model vehicles. Basell's PP employs 1-nm thick flakes of day that render it stiffer, lighter, and less brittle in cold temperatures than conventional polyolefin composites filled with far larger micrometer-scale particles of talc.

- GM says the PP's enhanced strength means lighter parts can be used

- Putties used to fill gaps between stealth body panels on advanced fighter planes carry about 40 to 50% carbon fiber by weight, making them brittle. With carbon nanotubes, the job can be done with 1%-2% loading

Nanophase Technologies Corp [67]

- Nanocrystalline materials manufacturer
- Nanocrystalline materials consist of ceramic and metallic materials in powder form, with particle sizes measured in nanometers - billionths of a meter. The near-atomic size of these particles, combined with the dynamic properties of surface atoms, mean they can be used to alter and enhance the performance of raw materials, such as zinc, aluminum and iron.
- The company's materials improve everyday products such as catalytic converters for automobiles, or they improve the characteristics of wear-resistant floors.
- Independent tests show sunscreens using its nanocrystalline titania (a non-irritating alternative to sun-blocking chemicals) provide higher SPF protection using less material than conventional products, with no skin-whitening effect.

Polymer Composites [68]

- Kings Stormwater Channel Bridge in Riverside County California
- Though "polymer matrix composites" (fibers like carbon or glass encased in plastic) have found their way into a smattering of smaller structures in the past decade, the new bridge is the first to face the test of highway traffic and long-haul trucks. It boasts a fiberglass composite deck with a thin veneer of special concrete supported by carbon-fiber composite tubes just 355 millimeters in diameter. The materials are so lightweight two men can do what normally requires a crane.

Nanocomposites [69](using nanoparticles of clay to raise polymers)

- According to the April 2001 issue of *Mechanical Engineering* magazine, automobile manufacturers are investigating the use of nano-composites developed with montmorillonite clay for exterior body panels and interior components such as dashboards and instrument panels. [70]

- In the late 1980s, Toyota Central Research Labs in Japan teamed up with Ube Industries Ltd., a Japanese resin supplier, to produce a new composite polymer, consisting of nylon 6 interspersed with layers of montmorillonite, a layered silicate clay. The clay greatly improved the mechanical properties of the nylon with very small filler loading.

- Very low loadings of filler—less than 5 % by weight—produced big gains in properties, compared with levels of 30 % or higher with reinforcements of glass and talc.

- An attractiveness is weight savings as a major advantage of TPO nanocomposites, because of loadings of less than 5 percent.

- Looking at individual parts on the exterior, it is estimated automotive producers can get from 7 to 21 % reduction in weight.

**Nanoelectronics and Computer Technology**

Potential breakthroughs include (a) nanostructured microprocessor devices that continue the trend in lower energy use and cost per gate, thereby improving the efficacy of computers by a factor of millions; (b) communications systems with higher transmission frequencies and more efficient utilization of the optical spectrum to provide at least ten times more bandwidth, with consequences in business, education, entertainment, and defense; and (c) small mass storage devices with capacities at multi-terabit levels, a thousand times better than today;

Nanoscale approaches to computing, such as molecular computing—which uses single-molecule switches to process data—and quantum computing—which uses single electrons—offer hope that integrated circuits can continue to keep up with Moore's law, which predicts that circuit size will halve, and speed therefore double, every 18 months. [71] Depending on their size and shape, the electronic properties of carbon nanotubes can be metallic or semiconducting.

IBM

***IBM nanoscience and technology group*** [72]

- Research has focused on two areas, carbon nanotubes and local oxidation of semiconductors and thin metal film
    - Carbon
    - Carbon nanotubes are extremely thin, hollow cylinders made of carbon atoms.
    - Oxidation
    - IBM is undertaking research on the capability to oxidize metals and semiconductors with nanometer-scale resolution, which the company feels opens a variety of possibilities to improve current electronic devices such as field-effect transistors and allows the fabrication of novel electronic devices such as single-electron transistors.
- Moore's Law states that the number of transistors that can be packed on a chip doubles every 18 months, but many scientists expect that within 10-20 years silicon will reach its physical limits, halting the ability to pack more transistors on a chip.
    - IBM scientists developed a breakthrough transistor technology that could preview how computer chips can be made smaller and faster than what is currently possible with silicon
    - IBM researchers have built the world's first array of transistors out of carbon nanotubes -- tiny cylinders of carbon atoms that measure about 10 atoms across, are 500 times smaller than today's silicon-based transistors and are 1,000 times stronger than steel. The breakthrough bypasses the slow process of manipulating individual nanotubes [73]

***Nanocrystal Superlattice research at IBM*** [74]

- Engineers have long increased storage capacity by shrinking the magnetic grains in the films, so each bit of stored data takes up less space. But there's a limit to this process: Many magnetic materials, such as cobalt, lose their magnetic behavior when particles shrink below about 10 nanometers. And particles that do maintain their strong magnetic behavior tend to clump together instead of forming an even sheet.
- For Today's hard disks, Manufacturers essentially spray-paint magnetic material onto a surface under vacuum and bake it. That leaves a material full of 15- to 20-nanometer magnetic grains whose magnetic orientation can be aligned by a recording head positioned just above it. Typically, a bit of information is stored as the common orientation of hundreds of those grains.
- IBM researchers have created tiny carbon-coated metallic particles--each just 4 nanometers, or billionths of a meter, across--that they assemble into a thin sheet and bake into a magnetic film that could be used in hard disk drives. The researchers started by concocting a solution that included two metal salts--one containing iron atoms, which are hungry for electrons, the other platinum atoms capable of donating electrons. As the salts dissolved, the iron atoms turned to the platinums for electrons, causing the atoms to begin assembling themselves into a ball. Also in the brew were soap molecules, oleic acid, and oleyl amine. As the particles grow, the soap molecules glommed onto the metal particles and stopped growth at 4 nanometers.
- While this still needs to be made compatible with the technology used for writing and reading bits, it indicates that magnetic recording could be carried down to near molecular length scales

***Nanoelectromechanical systems (NEMS)*** [75]

- The next step beyond microelectromechanical systems, NEMS are characterized by small dimensions, where the dimensions are relevant for the function of the devices. Critical feature sizes may be from hundreds to a few nanometers.
    - The importance of MEMS technology is not so much the size, but rather the use of planar processing technologies, related to those used in the fabrication of electronic integrated circuits, to simultaneously "machine" large numbers of relatively simple mechanical devices in an integrated fashion.
- NEMS systems that are defined by lithographic approaches are approaching the dimensions of carbon nanotubes, but can be formed in a range of materials and integrated with electronic and optical systems to create highly functional devices. Interfacing to naturally occurring functional molecules such as receptor molecules, membrane pores, motor molecules, and other functional molecular systems presents exciting new possibilities.

**Nanotechnology and biochemical detection**

Monitoring heavy metal contaminants—such as lead, mercury and cadmium—in rivers and wells requires multiple trips to the lab for analysis with expensive and bulky equipment. Joseph T. Hupp, Northwestern University

A team of chemists headed by Joseph T. Hupp at Northwestern University has a more efficient method that could be adapted to make a portable device for testing samples in the field.

- Hupp's group starts with nanoscale-sized particles of gold, each smaller than a virus. They then coat the particles with molecules that are able to bind with the heavy metals. Water containing the particles naturally assumes a deep shade of red. But if, for example, lead ions are present, they attach to the receptors, causing the gold particles to aggregate and turn the water blue.
- The greater the lead concentration, the more dramatic the color change. Then, to determine the exact quantity of heavy metal in the water, the Northwestern researchers measure its absorption of ultraviolet light. While not as sensitive as standard tests, the processes method's speed and low cost make it an attractive alternative. [76]

Nicholas Abbott, University of Wisconsin

Today, the most common field instrument for detecting environmental toxins is the portable gas chromatograph, which costs thousands of dollars and weighs upwards of 50 pounds. Nicholas Abbott (University of Wisconsin) has created a novel sensor that uses liquid crystals to detect environmental contamination. [77] It is a sensor that uses *liquid crystals to* detect environmental contamination.

- Abbott's device consists of three components: a bottom layer of gold patterned with nanoscale grooves, receptor molecules embedded in that layer, and a top layer of liquid crystals attached to the receptors by a loose hydrogen bond
- Abbott says his detector is not only cheaper to manufacture, but more portable and easier to use: a person could wear the device as a color-changing badge, similar to those that measure radiation exposure.
- Although the device currently detects only gaseous compounds, Abbott hopes to develop a version that works with fluids
- Today, the most common field instrument for detecting environmental toxins is the portable gas chromatograph, which costs thousands of dollars and weighs upwards of 50 pounds, although devices that detect only one or two compounds may weigh as little as ten or fifteen pounds
- This alternative device, created at the University of Wisconsin, consists of three components: a bottom layer of gold patterned with nanoscale grooves, receptor molecules embedded in that layer, and a top layer of liquid crystals attached to the receptors by a loose hydrogen bond.

- The device currently detects only gaseous compounds, but there is ongoing research to develop a version that works with fluids

**Nanotechnology and reducing emissions:**

- Research has been done at MIT examining how Nanocrystalline perovskites can be used in the catalytic combustion of methane in order to reduce air emissions. [78] Catalytic combustion of methane is an attractive alternative to gas-phase homogeneous combustion, since it can stabilize flames at lower fuel-to-air ratios, thereby lowering flame temperatures and significantly reducing NOx emissions.
- Developed by the oil industry, the ordered mesoporous material MCM-41 (known also as "self-assembled monolayers on mesoporous supports," SAMMS), with pore sizes in the range of 10 - 100 nanometers, is now widely used for the removal of ultrafine contaminants. [79]
    - Research has demonstrated that MCM-41 is also effective in removing sulfur from heavy oils, such as slurry oil.
- Nanotechnology's potential benefits for transportation are broad and pervasive: lighter, more efficient cars using nanostructured materials; corrosion-free bridges and no-maintenance roads; tiny "traps" that remove pollutants from vehicle emissions; and robotic spacecraft that can explore the solar system and yet weigh only a few pounds. Among the potential transportation breakthroughs are the following: [80]
    - Nanoparticle-reinforced materials that replace metallic components in cars, and
    - Nanosensors that could be used to monitor vehicle emissions and to trap any pollutants. Carbon-based nanostructures that serve as "hydrogen supersponges" in vehicle fuel cells.

**Nanotechnology and water purification**

- PMG Medica has a patent on a nanotechnology to totally exterminate microbes in water [81]
    - Testing the extermination of microbes at a density of half a billion microbes per millimeter, found the patented product could completely eliminate them in 10 seconds.
- Nanoscale gold particles have been used in the US to provide an early warning of heavy metal pollution in water - in Chicago, many low income housing developments contain lead levels which are very difficult to detect until they reach a toxic stage, but by using nanoscale materials, we can pick up on pollutants well before they become a health risk. [82]

**Nanotechnology and catalysts**

- Lightyear Technologies is working on chemical catalysts to purify water. [83]
    - Catalysis could arguably be the most important technology in modern society since it enables the production of a wide range of materials and fuels.
    - However, the full extent of the nature of the surface of nanoparticles used in catalysis is not completely understood;
    - However, Because catalytic reactions take place at the surface of the material, therefore the more surface there is, the better
    - Catalysis can be used in the clean-up of emissions from cars
    - The pharmaceutical sector uses catalysis on a much smaller scale, producing high added value molecules

Nanoscale Materials [84]

- http://www.nanmatinc.com/
- Company founded to develop and commercialize reactive nanoparticles (RNPs) and other related technologies.

- The company is now preparing two nanocrystal-based products – a skin cream designed to protect against chemical and environmental hazards and a spray applied from a fire extinguisher-type canister that provides similar protection.
- The company is also researching other possible commercial applications for its nanocrystals. They could be used in home air and water filtration systems, as catalysts for petrochemical processing and as magnetic storage materials for computers and disk drives.

**Nanotechnology and reverse osmosis**

- Nanotechnology has the potential to improve agricultural yields for an increased population, provide more economical water filtration and desalination, and improve renewable energy sources, such as solar energy conversion. A recently tested flow-through capacitator with aligned carbon nanotube electrodes can desalt seawater with 10 times less energy than state-of-the-art reverse osmosis. [85]

**Nanotechnology and aerospace**

Nanostructuring is critical to design and manufacture of lightweight, high strength, thermally stable materials for planes, rockets, space stations, and planetary/solar exploratory platforms.

An ambitious project sits in the Massachusetts Institute of Technology's Department of Aeronautics and Astronautics. With NASA support, MIT engineers are building a microrocket that works more or less like the engine on the space shuttle. NASA hopes to use the microrocket for attitude control on future space vehicles. MIT envisions this liquid oxygen/ethanol rocket engine to be a wafer-like structure approximately 1.5 cm long, 1.2 cm wide, and about 2.5 mm thick, producing a thrust of a little over three pounds. This means it would have a thrust to weight ratio exceeding 10,000. [86]

**Nanotechnology and energy**

<u>Photovoltaic applications</u>

Although most current PV production is based upon crystalline and amorphous silicon technologies, research is now focusing upon new technologies that may result in significant reductions in PV costs, and / or improvements in efficiency. 2 big areas:

- Quantum well solar cells
  - Quantum wells are ultra-thin layers (nanostructures) of narrower band-gap semiconductor (the well) grown between regions of higher band-gap material (the barrier) by modern crystal growth technologies such as molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE).
- Dye sensitized nanocrystalline devices
  - This example of nano-structured materials for PV applications concerns the use of nanoporous metal oxide films.
  - These novel photoelectrical solar cells have attracted considerable interest because of their potential as low cost solar cells. In contrast to conventional solid state solar cells, which depend on advanced processing of very high purity semiconductors and are therefore relatively expensive to make, the nanocrystalline solar cell is fabricated from cheap, low purity materials by simple and low cost procedures.[87]
- Swiss firm: Greatcell Solar S.A,
  - A daughter company of Leclanche SA, Greatcell has developed a new type of photovoltaic cell based on results carried out at the Swiss Federal Institute of Technology in Lausanne. These dye sensitized photovoltaic cells represent a completely new family of PV devices based on nanotechnology. The electric current is generated by light-absorbing dye molecules imbedded in a nanocrystalline titanium oxide film. The unique characteristics of the Greatcell devices make them the optimal solution for many indoor applications. Their

main advantages compared to crystalline and amorphous silicon cells are: High performance at low light levels and for diffuse illumination; Optimal performance under artificial light, i.e. fluorescent or incandescent light sources; Highly transparent devices with excellent optical quality available; Stable output voltage even at low light levels. [88]

Other Energy Applications

- Northwestern's Center for Transportation Nanotechnology, is looking to do research on:
    - Improved catalysts can reduce or eliminate the emission of pollutants from engines
    - Small chemical sensors with parts smaller than a human hair can now be designed to detect trace chemicals
    - Nanostructured Fuel Cells
    - As example:
        - a) New materials designed to have superior properties (stronger, lighter) using materials with nanoscale dimensions will lead to faster, cheaper and safer transportation.
        - b) Improved catalysts can reduce or eliminate the emission of pollutants from engines that lead, for instance, to smog.
        - c) Miniature sensors and machines will be incorporated in ever increasing numbers within structures, engines and other components to provide better understanding of their condition and detect and report early signs of wear.
        - d) New photonic nanodevices can replace the heavy and costly RF transmission equipment on board aircraft, ships or satellites or be exploited for inexpensive remote control of vehicles.
- MonteEdison [89]
    - In the field of nanotechnology, the Company started a three-year program, in cooperation with the El.B.A. Foundation and the Biophysics Institute of the University of Genoa, in Italy, for the purpose of studying the application potential of these technologies in the electric power industry, particularly in the development of photosensitive elements.
- Several chemical manufacturing companies are developing a nanoparticle-reinforced polymeric material that can replace structural metallic components in the auto industry. Widespread use of those nanocomposites could lead to a reduction of 1.5 billion liters of gasoline consumption over the life of one year's fleet of vehicles and reduce carbon dioxide emission by more than five billion kilograms annually. [90]
- The US Department of Energy is exploring how electric charges move at the nanoscale. [91] A hope is that these research studies could lead to advances in energy conversion devices such as those that convert sunlight into electricity, and new "molecular electronics" for tinier, faster computer circuits.
    - NREL is currently conducting research in dye-sensitized nanocrystalline solar cells. These will produce electricity from the Sun more efficiently than solar cells using current technology, the most efficient of which convert only 32 % of the Sun's energy to electricity.

**Companies in nanotechnology development and manufacturing (not a complete listing):**

| | |
|---|---|
| **Nanometrics** | ▪ Designs, manufactures and markets advanced thin film and overlay metrology systems.<br>▪ http://www.nanometrics.com/ |
| **Nanocor** | ▪ Utilized technology that disperses nanoscale particles of chemically modified clays into plastic resins, improving strength, heat stability and barrier properties.<br>▪ Company's nanocomposite technology being used by Honeywell for its new Aegis(TM) products.<br>▪ http://www.nanocor.com/ |
| **Physical Sciences Inc.** | ▪ Developing an advanced carbon nanotube membrane for direct methanol fuel cells.<br>▪ Research effort hopes to result in a power density increase of as much as 20% for the DMFC and will substantially improve the performance and cost effectiveness of direct methanol fuel cells.<br>▪ http://www.psicorp.com/html/new/carb-ntube.htm |
| **Nanomaterials** | ▪ Involved in the research and development of unique semiconducting sensors for both toxic and combustible gases.<br>▪ http://www.nrcorp.com/ |
| **Hyperion Catalysis** | ▪ Carbon nanotube development.<br>▪ Graphite nanotube filled plastics are finding application in areas where dissipation of electrostatic charges is critical – such as automotive fuel systems and computer disk drives.<br>▪ http://www.fibrils.com/ |
| **Carbon Nanotechnologies Inc.** | ▪ Leading developer of single- wall carbon nanotubes – buckytubes.<br>▪ CNI has intellectual property for end-of-tube and sidewall derivatization of buckytubes.<br>▪ http://www.cnanotech.com/4-0_about.cfm |
| **NanoPowders** | ▪ Nanosized and ultrafine metal powders are raw materials used in the production of Microelectronic Passive components.<br>▪ http://www.nanopowders.com/ |
| **Argonide Nanometals Corporation** | ▪ Company focus is the production of novel nano metal powders and certain ceramics as well as applications of them for catalysis, nanodevices, nanoelectronics, nanosensors, powder metallurgy, corrosion and wear resistant coatings and as additives to lubricants. In addition to in-house R, D and E efforts, firm's nano focus involves a cooperative research and development program (CRADA) with the U. S. Department of Energy.<br>▪ http://www.argonide.com/ |
| **Nanogen, Inc.** | ▪ Company has developed technology that integrates advanced microelectronics and molecular biology on proprietary semiconductor microchips.<br>▪ http://www.nanogen.com/ |
| **Luna Nanomaterials** | ▪ Research focus is on carbon fullerene materials (buckballs), specializing in endohedral metallofullerenes-- hollow molecules of carbon atoms that encapsulate various metal and rare earth elements.<br>▪ http://www.lunananomaterials.com/ |
| **Powdermet Inc.** | ▪ Powdermet designs, develops, and manufactured nanoengineered meal and ceramic materials using a "nanolaminate" particle approach. |

| | |
|---|---|
| | Powdermet has combined two approaches to nanomaterials, nanoparticles and vapor deposition technology, to synthesize ulk 3-D nanocomposites from metals and ceramics using a powder metallurgy approach.<br>▪ http://www.powdermetinc.com/ |

**Other General Nanotechnology Resources**

| | |
|---|---|
| Nanotech at Harvard | http://www.researchmatters.harvard.edu/topic.php?topic_id=186 |
| MIT Nanostructured Materials Lab | http://web.mit.edu/nano/www/home.html |
| Northwestern Institute for Nanotechnology | http://www.nanotechnology.northwestern.edu |
| CENTER for Nanoscale Science and Technology – Rice University | http://cnst.rice.edu/ |
| The Foresight Institute | http://www.foresight.org/ |
| Loyola Nanotechnology database | http://itri.loyola.edu/nanobase/ |
| Small Times | http://www.smalltimes.com/index.cfm |
| Nanoscale Science and Technology | http://www.vjnano.org/nano/?jsessionid=2442621008967931784 |
| University of Wisconsin – Materials Research and Engineering Center | http://www.mrsec.wisc.edu/ |

## Endnotes

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