CHAPTER 4

Making the World

Fewer calories, more energy — A new design mentality — No limits to innovation — Distributing control — Organizations that learn — Getting as smart as clams — Repurifying Swiss drinking water — Ephemeralization — Born-again materials

INDUSTRY MAKES THINGS. IT TAKES MATERIALS — GENERALLY OUT OF THE ground — and processes them into desired forms. These objects are distributed, sold, used, discarded, and then typically dumped back in or onto the ground. Because economic consumption doesn't create or destroy matter[1] but only changes its location, form, and value, the same tonnages that were mined from the ground as resources, treated, transported, made into goods, and distributed to customers are then hauled away again as waste or emitted as pollution.

For the average American, the daily flows of materials (other than water) total more than twenty times a person's body weight, nearly all of it waste. But that waste can be greatly reduced without compromising our well-being. Any improvement that provides the same or a better stream of *services* from a smaller flow of *stuff* can produce the same material wealth with less effort, transportation, waste, and cost.

MORE ENERGY-EFFICIENT MANUFACTURING

For centuries, even millennia, engineers have sought to reduce industry's use of energy and resources. The previous industrial revolution sped the transition from Newcomen's 0.5 percent efficient steam engine to today's better than 50 percent efficient diesel engines. For decades, the energy used to make a given product has been falling by typically a percent or two a year — faster when energy prices rise, slower when they fall. Yet at each stage of the industrial process, a host of opportunities still exists for doing more and better with much, much less. Even in the most efficient countries and industries, opportunities to wring out waste and improve product quality, as human ingenuity develops new technologies and finds better ways to apply them, are expanding faster than they're being used up. This is partly because technology improves faster than obsolete factories are replaced, but often it's just because people and firms aren't yet learning as fast as they could and should. The possible improvements will no doubt lose momentum at some point, but it's no more in sight than is the end of human creativity.

To look at only one example, chemical manufacturing uses heat and pressure, first to cause reactions that shift and shape molecules into desired forms, then to separate those products from undesired ones. Chemical engineers have been saving energy and materials costs for over a century, cutting U.S. chemical firms' energy intensity in half just since 1970. They've plugged steam leaks, installed thermal insulation, and recovered and reused heat. But there's still more to be saved — far more. "Pinch technology" helps deliver heat at just the temperature required for the process and then recover it. These two improvements can often save another half or more of the remaining energy, yet pay for themselves quickly — within six months in typical retrofits.[2] Meanwhile, designer catalysts are being tailored to help make specific chemical reactions take place faster and more efficiently, yielding less mass of the undesired products that in fine chemicals often weigh 5 to 50, and in pharmaceuticals 25 to 100-plus, times as much as the desired product.[3]

No industry lacks potential for radically better energy efficiency, not even the world's most advanced major business, the making of microchips — the highest-value-added sector of U.S. manufacturing,[4] and soon to be one of the world's largest employers. Chipmaking plants are consistently designed so poorly that most of their energy can be saved with 100-plus percent typical after-tax returns on retrofit investments, better operations, and faster, cheaper construction of new plants.[5] For example, a large Asian chip-assembly plant in 1997 cut its energy bills by 69 percent per chip in less than a year; a Singapore chipmaking plant between 1991 and 1997 cut its energy use per wafer by 60 percent with half the paybacks under twelve months and four-fifths under eighteen months; another saved $5.8 million per year from $0.7 million of retrofit projects.[6] Chipmakers, with $169 billion worth of new plants on the drawing boards worldwide,[7] are just discovering that highly efficient plants, and the design and management philosophy they reflect, will allow them to outcompete their rivals.

The potential for saving energy, resources, pollution, waste, and money in the industrial realm would take many specialized books to describe, because its range of activities is so diverse and complex. The U.S. chemical business alone comprises more than 30 industries producing over 70,000 distinct products in more than 12,000 factories.[8] However, if considered in sufficiently general terms, the methods to increase industry's energy and material productivity can be classified into at least six main categories, which often reinforce one another:

- design
- new technologies
- controls
- corporate culture
- new processes, and
- saving materials

DESIGN

The whole-system approach applied to Hypercars can be applied in the rest of industry, too: Virtually all the energy-using equipment now in use was designed using rules of thumb that are wrong. Asking different questions, much as the scientist Edwin Land did when he described invention as "a sudden cessation of stupidity," can suggest areas to be targeted for innovation. This can achieve large energy savings in such commonplace equipment as valves, ducts, fans, dampers, motors, wires, heat exchangers, insulation, and most other elements of technical design, in most of the technical systems that use energy, in most applications, in all sectors. This new efficiency revolution, much of it retrofittable, relies not so much on new technology as on the more intelligent application of existing technology, some of which dates back to the Victorian period.

Sometimes the best changes in design are the simplest. Enabling America's half million laboratory fume hoods to use 60–80 percent less fanpower yet become even safer is largely a matter of changing the position of one louver.[9] In the mundane but very costly task of removing contaminated air from cleanrooms, a new mechanical flow controller,[10] using a single moving part operated solely by gravity and airflow, can reduce energy use by around 50–80 percent, reduce total construction cost, and improve safety and performance. New geometries can double the efficiency of sewage pumps[11] and quintuple that of aerators.[12] Such simple but large opportunities abound in the heaviest industries, too. Steel slabs are normally cast far from the rolling mills that make them thinner, so by the time they arrive to be rolled, they need to be reheated; moving the two processes closer together saves about 18 percent of that reheat energy.[13] The U.S. glass industry's goal of halving its process energy consumption by 2020[14] will depend partly on losing less heat from regenerative furnaces. R&D so far has focused mainly on the smallest loss — the 23 percent that is dissipated up the stack. But why not first address cutting the biggest loss — the 40 percent escaping through the furnace wall, which can be superinsulated?

It may finally take a wakeup call to bring about a shift of design mentality in some entrenched industries. Few believed that Weiss, a Hamburg oil re-refinery, could eliminate its unlicensed discharge into the harbor until Greenpeace activists got impatient, plugged up the pipe, and announced that the plant had two hours to figure out how to clean up before its tanks started overflowing. The plant shut down for a half year, completely redesigned its refining process, and hasn't discharged effluent since.[15]

NEW TECHNOLOGIES

New materials, design and fabrication techniques, electronics, and software can fuse into unexpected patterns — technologies more powerful than the sum of their parts. From superefficient cooling coils to switched-reluctance motors (which can continuously adjust their software for peak efficiency under all operating conditions), smart materials to sophisticated sensors, rapid prototyping to ultraprecision fabrication, improved power-switching semiconductors to atomic-scale manipulation, microfluidics[16] and micromachines,[17] revolutions are under way in myriad technical arts and sciences.

Innovation seems in no danger of drying up. Technologies available today can save about twice as much electricity as was feasible five years ago, at only a third the real cost. That rate of progress has been consistent for the past fifteen to twenty years. Much of the continuing improvement in energy efficiency is due to ever better technologies for wringing more work out of each unit of energy and resources. Lately, though, the changes in design mentality — the ways to apply these established technologies — have become even more critical.

Each time practical limits to innovation seem to be approaching, or even limits imposed by the laws of physics, someone devises a way to evade those limits by redefining the problem. Generations of power engineers knew their generating plants couldn't ever be more than 40-odd percent efficient because of Carnot's Law, which first described the theoretical limits. Surprise: Now you can buy off-the-railcar combined-cycle gas turbines that are about 60 percent efficient, using a different thermodynamic cycle not subject to Carnot's Law. Fuel cells can do even better. And of course the rest, the "waste" heat, need not be wasted. Recovering it can raise the useful work extracted, mostly as electricity, to more than 90 percent of the original fuel energy.

CONTROLS

Information technologies provide large savings as various industries adopt them. A coal-fired power station that ran the old way — hard-hatted guys with big wrenches ran around adjusting valves as a supervisor scanned a wallful of hydraulic gauges — hired a couple of young engineers fresh out of Georgia Tech. They harried their boss into letting them buy a two-hundred-dollar Radio Shack portable computer on which they wrote a simple program to help optimize the plant's operations. Their initiative saved millions of dollars in the first year. The rookie engineers soon found themselves telling their story to the board of directors, launching a transformation in the culture of the Georgia Power Company.[18]

Most factories throughout the world still lack such simple, gross-scale optimization and controls. Moreover, many existing controls aren't properly used. Controls should measure what's happening now, not what happened an hour ago, because problems not discovered and fixed immediately cause waste. The Toyota empire was built on revenues garnered from Sakichi Toyoda's "self-monitoring" looms, which shut down instantly if a thread broke, before they could make defective cloth. This obvious principle is still often ignored in those industries where delayed feedback is the most costly. Distillation columns use 3 percent of total U.S. energy to separate chemical and oil products, but most operators, instead of continuously monitoring the purity of product as it emerges, test only occasionally to make sure samples meet specification. Between tests, the operators, flying blind, often feed the same material back through the column more times than necessary — using 30–50 percent excess energy — to be really sure the product will pass the test. Better controls that measure the purity actually coming out and keep fine-tuning the process for the desired results could cut that waste about in half.[19] A civilization that can robotically measure the composition of rocks on Mars should be able to measure the composition of chemicals in a pipe on Earth.

Measurement and control intelligence can be distributed into each piece of manufacturing equipment so that each part of the process governs itself. Reactions can be kept at the right temperature, machine tools fed to cut at the optimal rate, textiles heated until they're dry but not baked. The more localized the control and feedback, the more precise the levels of control. Ubiquitous microchips now permit not just such simple controls but also the construction of neural networks that learn, and the use of fuzzy logic that makes eerily smart decisions.

The emerging next step in distributed intelligence is self-organizing systems of all kinds. Hierarchical control systems have one centralized boss, human or computerized, telling everyone what to do and enforcing commands through layers of authority. Distributed intelligence, in contrast, uses many decentralized decision makers of comparable power, interpreting events under shared rules, interacting with and learning from each other, and controlling their collective behavior through the interaction of their diverse local decisions, much like an ecosystem works. Kevin Kelly, in his book *Out of Control,* describes how this ecosystem-like model, where many small parts join together to create a highly adaptive whole, is gradually taking over the world as complex systems organize and adapt in coevolution with their changing environments, just like life itself. Thus the "world of the made" will increasingly come to resemble the "world of the born": technical artifacts will start being organized and controlled more and more by biologic, because biological systems already have evolved successful design solutions.[20]

In these and other important ways, designers are beginning to incorporate the billions of years' design experience reflected in biological principles into industrial applications. These are being carried out not merely in process design but also in areas of system architecture and control. The plant whose operators rely on luck or intuition to optimize complex processes with hundreds of interacting variables is already losing out to the plant whose operators have turned to powerful computers equipped with artificial intelligence and "genetic algorithms," which evolve the fittest solutions by a mathematical version of Darwinian natural selection. The operator scanning endless tables of numbers won't understand what's happening as well as the operator whose computer graphics let her see at a glance what's happening in the plant, how to improve it, and how to design the next plant even better. Ultimately, if factories become really smart, they won't need special control systems. They'll guide even the most awesomely complex processes with the insouciant ease with which self-controlling cells make their myriad biochemicals, or self-controlling ecosystems, adapt to their changing environments.

CORPORATE CULTURE

A business that functions as a learning organization — rewarding measurement, monitoring, critical thought, and continuous improvement — will always outpace a corporate culture peopled by dial-watchers and button-pushers. A business that takes advantage of powerful tools for measurement, simulation, emulation, and graphic display can turn the design and operating processes from linear — require, design, build, repeat — to cyclic — require, design, build, *measure, analyze, improve,* repeat. A business that ignores measurement will inevitably fall behind in making useful and cost-saving discoveries — like the chemical company that for decades had been unwittingly running a forty-kilowatt electric heater under its parking lot year-round to melt snow. Nobody remembered or noticed the device until measurement found that the energy books didn't balance, and the wiring was traced to track down the discrepancy.

Many manufacturing firms are unwittingly experiencing similar financial drains in their compressed-air systems: You can walk through their plants listening to the money hissing out of the leaks. Improved compressed-air maintenance and hardware typically yield savings approaching 50 percent with six-month paybacks.[21] But if nobody pays attention, bad housekeeping persists. It typically gets fixed only when someone wanders in on a weekend, notices the compressor turning on to replenish pressure being lost through leaks, and happens to wonder why the compressor is working at all when nobody else is.

Sometimes it's clear to everyone that something's wrong, but no one can figure out why. A southwestern adobe hotel, long passively cooled, suddenly started overheating. Just as the owner was about to buy a big air conditioner, a guest, who happened to be an Israeli solar expert, diagnosed the problem: the walls, originally whitewashed, had been painted brown.

You might think that such obvious answers should be easily worked out in modern factories full of smart engineers. But they aren't.[22] Sometimes equipment is improperly installed because it is mislabeled at the factory. In 1981, Pacific Gas and Electric Company built the Diablo Canyon nuclear power plant's major pipe supports the wrong way around, costing billions of dollars to fix, because someone had reversed the blueprint. The twenty-year, $2.5 billion Hubble Space Telescope project launched a misshapen mirror into space because of a sign error in an algebraic equation. Or to pick a mundane case, measurements on three thousand Southern California houses found one-fifth were miswired, with either no functional ground or ground and neutral interchanged. The electricians who wire factories are equally fallible.

For decades, even after computer memory had become so cheap that the original rationale had long since vanished, skilled computer programmers, often under direct orders from their superiors, saved money by writing dates with two year digits instead of four — snarling the world's software and hardwired chips into the Year 2000 bug. The costs of fixing that are so incalculable that they may erase much of all productivity gains from worldwide computerization. Fortunately, most mistakes are more farcical than economy-busting: To test a high-speed train design, British Rail borrowed the Federal Aviation Administration's gun that fires dead chickens at aircraft windshields to ensure they can withstand a bird strike. BR's engineers were horrified when the test chicken went through the windshield, through the driver's chair, and made a big mess on the back wall. The FAA checked the protocol and recommended a retest — "but this time, make sure the chicken has first been thawed."

NEW PROCESSES

Process innovations in manufacturing help cut out steps, materials, and costs. They achieve better results using simpler and cheaper inputs. In practically every industry, visionaries are improving processes and products by developing highly resource-efficient materials, techniques, and equipment. Even in iron- and steelmaking, one of the oldest, biggest, and most resource-intensive of the industrial arts, researchers have discovered ways to reduce energy use by about four-fifths with better output quality, less manufacturing time, less space, often less investment, and probably less total cost.

A particularly exciting area of leapfrog improvements is the potential to replace high-temperature processes with gentler, cheaper ones based on biological models that often involve using actual microorganisms or enzymes. Such discoveries come from observing and imitating nature. Ernie Robertson of Winnipeg's Biomass Institute remarked that there are three ways to turn limestone into a structural material. You can cut it into blocks (handsome but uninteresting), grind it up and calcine it at about 2,700°F[23] into Portland cement (inelegant), or feed it to a chicken and get it back hours later as even stronger eggshell. If we were as smart as chickens, he suggested, we might master this elegant near-ambient-temperature technology and expand its scale and speed. If we were as smart as clams and oysters, we might even do it slowly at about 40°F, or make that cold seawater into microstructures as impressive as the abalone's inner shell, which is tougher than missile-nosecone ceramics.[24]

Or consider the previously noted sophisticated chemical factory within every humble spider. Janine Benyus contrasts arachnid with industrial processes:

> The only thing we have that comes close to [spider] silk . . . is polyaramid Kevlar, a fiber so tough it can stop bullets. But to make Kevlar, we pour petroleum-derived molecules into a pressurized vat of concentrated sulfuric acid and boil it at several hundred degrees Fahrenheit in order to force it into a liquid crystal form. We then subject it to high pressures to force the fibers into alignment as we draw them out. The energy input is extreme and the toxic byproducts are odious.
>
> The spider manages to make an equally strong and much tougher fiber at body temperature, without high pressures, heat, or corrosive acids. . . . If we could learn to do what the spider does, we could take a soluble raw material that is infinitely renewable and make a superstrong water-insoluble fiber with negligible energy inputs and no toxic outputs.[25]

Nature's design lessons can often be turned to an unexpected purpose. Watching a TV report on sea otters soaked by the 1989 *Exxon Valdez* oil spill, Alabama hairdresser Philip McCrory noticed that otter fur soaked up oil extremely well. This was a good trait for keeping the otter dry in clean water, but for the same reason, fatal when the otter had to swim through oil. Could the characteristic be exploited to help pull oil *out* of the water? Could comparably oil-prone human hair do the same thing? McCrory took hair swept from his salon floor, stuffed it into a pair of tights to make a dummy otter, and threw it into a baby pool filled with water and a gallon of motor oil. In two minutes, he reported, "the water was crystal clear." Salon clients who worked for NASA put him in touch with an expert there who ran a larger-scale test. It found that "1.4 million pounds of hair contained in mesh pillows could have soaked up the entire *Exxon Valdez* oil spill in a week," saving much of the $2 billion Exxon spent to capture only 12 percent of the 11 million gallons spilled.[26]

In nature, nothing edible accumulates; all materials flow in loops that turn waste into food, and the loops are kept short enough that the waste can actually reach the mouth. Technologists should aim to do the same. One of most instructive of such loop-closings occurred in 1988 when the University of Zürich decided to revise the 1971-vintage elementary laboratory course accompanying the lectures in introductory inorganic, organic, and physical chemistry.[27] Each year, students' lab exercises turned $8,000 worth of pure, simple reagents into complex, nasty, toxic goop that cost $16,000 to dispose of. The course was also teaching the students once-through, linear thinking. So Professors Hanns Fischer and C. H. Eugster decided to *reverse the process* — redesigning some exercises to teach instead how to turn the toxic wastes back into pure, simple reagents. This would save costs at both ends and encourage "cycle thinking": "A few generations of science students trained in this domain," they suggested, "are the best investment for environmental protection by chemistry." Students volunteered vacation time for recovery, and by 1991, their demand for residues had outstripped the supply. Since then, the course has produced only a few kilograms of chemical waste annually — less than 100 grams per student per year, a 99 percent reduction — and cut net annual operating costs by around $20,000, or about $130 per student.

The chemical industry that will hire those students is already discovering multiple advantages from many other kinds of process innovations. For example, polyoxymetalates are emerging as a substitute for paper-bleaching chlorine, which can form dioxins. The new bleaching agents work as well, are easily regenerated, reduce pulp mills' effluent, increase the recycling of process water, and save half the electricity.[28] A small Oregon firm[29] developed a way to make foods like tomato paste using membranes instead of boiling; it's simpler, yields more product with higher quality, and uses 95 percent less energy. A molecular sieve, somewhat like Saran wrap with extremely tiny holes in it, concentrates food products *at room temperature* and retains the flavor, texture, and nutritional value destroyed by conventional boiling. A brine solution creates intense osmotic pressures — as much as four hundred pounds per square inch — that "suck" the water out of the food and across the membrane to dilute the brine. By not breaking up the large molecules that give tomato and other food purées their viscosity, direct osmosis retains texture with less water removal, yielding more of the intact food product, at higher value, per pound of input. Similar membranes are being applied to removing heavy metals and other toxic materials from landfill leachate. They can also remove 95 percent of the water from livestock manure, separating a lagoonful of toxic slurry into drinking-quality water plus a two-thirds-lighter fertilizer that's easier to transport.[30]

Some process innovations achieve many benefits at once. Architect William A. McDonough writes of an award-winning project for the DesignTex division of Steelcase, the largest American maker of office furniture:

> A few years ago we helped to conceive and create a compostable upholstery fabric — a biological nutrient . . . a fabric so safe one could literally eat it. . . . [European] government regulators had recently defined the trimmings of the [textile mills'] . . . fabric as hazardous waste. We sought a different end for our trimmings: mulch for the local garden club. . . . If the [naturally derived] fabric was to go back into the soil safely, it had to be free of mutagens, carcinogens, heavy metals, endocrine disruptors, persistent toxic substances, and bio-accumulative substances. Sixty chemical companies were approached about joining the project, and all declined. . . . Finally . . . Ciba-Geigy . . . agreed to join. With that company's help the project team considered more than 8,000 chemicals used in the chemical industry and eliminated 7,962. The fabric — in fact, an entire line of fabrics — was created using only thirty-eight chemicals. . . . When regulators came by to test the effluent, they thought their instruments were broken. After testing the influent as well, they realized that the equipment was fine — the water coming out of the factory was as clean as the [Swiss drinking] water going in. The manufacturing process itself was filtering the water.[31]

McDonough also reports a reduced production cost — no regulatory concerns, cheaper chemicals. The design concept, as he puts it, had "taken the filters out of the pipes and put them where they belong — *in the designers' heads.*" Everything that shouldn't be in the process had been eliminated by design. Design mentality can reshape production processes — and even the entire structure and logic of a business.

Ultimately, there's every indication that large-scale, specialized factories and equipment designed for product-specific processes may even be displaced by "desktop manufacturing." Flexible, computer-instructed "assemblers" will put individual atoms together at a molecular scale to produce exactly the things we want with almost zero waste and almost no energy expended. The technology is a feasible one, not violating any physical laws, because it is exactly what happens whenever nature turns soil and sunlight into trees, bugs into birds, grass into cows, or mothers' milk into babies. We are already beginning to figure out how to do this molecular alchemy ourselves: such "nanotechnologies" are doing surprisingly well in the laboratory.[32] When they take over at a commercial scale, factories as we know them will become a thing of the past, and so will about 99 percent of the energy and materials they use. The impact of that technology will dwarf that of any of the technical proposals in this book. Yet until nanotechnology is widely commercialized, industry should continue to explore how to reduce the massive flows of materials in its conventional production processes. Even if the nanotechnology revolution never arrives, savings nearly as great can still be achieved by focusing on the last and perhaps richest of our six near-term opportunities — materials efficiency.

Materials efficiency is just as much a lesson of biological design as the making of spider-silk: biomimicry can inform not just the design of specific manufacturing processes but also the structure and function of the entire economy. As Benyus notes, an ecologically redesigned economy will work less like an aggressive, early-colonizer sort of ecosystem and more like a mature one. Instead of a high-throughput, relatively wasteful and undiversified ecosystem, it will resemble what ecologists call a Type Three ecosystem, like a stable oak-hickory forest. Its economy sustains a high stock of diverse forms of biological wealth while consuming relatively little input. Instead, its myriad niches are all filled with organisms busily sopping up and remaking every crumb of detritus into new life. Ecosystem succession tends in this direction. So does the evolution of sustainable economies. Benyus reminds us, "We don't need to invent a sustainable world — that's been done already."[33] It's all around us. We need only to learn from its success in sustaining the maximum of wealth with the minimum of materials flow.

SAVING MATERIALS

If everybody in society is to have one widget, how many widgets must we make each year? Just enough to accommodate the number that break, wear out, or are sent away, plus however many we need to keep up with growth in the number of people. A key variable in production levels is clearly *how long* the widgets last. If the widgets are something to drink out of, we need a lot fewer ceramic mugs than paper or plastic cups, because the ceramic lasts almost forever unless we drop it, while the throwaways can be used only once or twice before they fall apart. If we make the ceramic mug unbreakable — especially if we also make it beautiful, so people enjoy having and using it — then it can last long enough to hand on to our great-grandchildren. Once enough such unbreakable mugs were manufactured to equip everybody with one, or with enough, relatively few would need to be made in each subsequent year to keep everyone perpetually supplied with the service that mugs provide.

Of course, if the ceramic mug is replacing disposable single-use paper or plastic cups, it keeps on saving those throwaway materials — made of forests and natural gas, birds and bayous — continually, for as long as the durable product is used instead. To be sure, half the fun of buying consumer goods is getting an ever-growing array of diverse items. But for most of what industry produces, this is hardly a consideration: Few of us collect washing machines, let alone steel billets or blast furnaces. In fact, washing machines not only cost money and take up space; they are used so relatively seldom, and repaired and remanufactured so little, that they are ten to eighty times more materials-intensive, per load of wash done, than are semicommercial machines, like those shared by the occupants of an apartment house.[34] Thus if even a modest fraction of people shared a washing machine, considerable materials flow could be avoided.

Items can be made even more economical if they're designed with the spare and elegant simplicity of a Shaker chair or a Ming vase. Good design needs less material to create a beautiful and functional object. Sculptural talent can be enhanced nowadays by computer-aided design, which calculates stresses and determines exactly how little material will make the object just as strong as we want — but no stronger. Often this requires severalfold less material. Strength can also be put only where it's needed: If an object will tend to break in one inherently weaker place, then it would be wasteful to make it excessively strong in another place. Conversely, small changes in design can produce vastly better function. Surgical bone screws used to pull out or break frequently, requiring further painful and costly operations. Then computer-aided engineering revealed that moving just a few percent of the metal from where it wasn't needed to where it was needed would make the screws hold tenaciously and hardly ever break.[35]

Another area for savings is the efficiency with which the raw material is converted into the finished object. That factor depends on the manufacturing process: Excess material needn't be removed to achieve the desired shape if all the material is *already* in the desired shape. "Net-shape" and "near-net-shape" manufacturing makes virtually every molecule of material fed into the process emerge as a useful product. (Pratt & Whitney used to scrap 90 percent of its costly ingots when making them into jet engine turbine blades, before it asked its alloy suppliers to cast the metal into bladelike shapes in the first place.)[36] Many processes implement scrap recovery to take back leftover material for reuse, but ideally, there will be no scrap because it will have been designed away at the outset.

Net-shape production unlocks a further way to save materials: consolidating many small parts, each individually fabricated, into a single large part molded to net shape. A toilet float/valve assembly, made mainly of cast or machined brass parts, was redesigned from 20 to 3 ounces, 14 parts to one molded plastic part, and $3.68 to $0.58 production cost. A 13-pound steel tricycle with 126 parts was redesigned to a 3-pound, 26-part plastic version at one-fourth the cost. A windshield-wiper arm was reengineered from 49 parts to one, at lower total cost, even though it was made of $68-a-pound carbon-fiber composites.[37] Since molded plastic parts produce a very low amount of manufacturing scrap compared to metals,[38] these examples actually saved far more input materials than they saved weight in the finished parts: The avoided scrap amplified the direct savings from parts consolidation. Moreover, not only plastics and clays can be molded to net shape, but also metal parts, through techniques like hydroforming, semiplastic forming, plasma spray, and powder metallurgy. These are increasingly eliminating machining scrap by eliminating machining.

Eliminating scrap takes many forms. In a sawmill, three-dimensional laser measuring devices can "visualize" how to slice up a log into the highest-value combination of lumber with the least sawdust, just as computers in clothing factories design complex cutting patterns to waste the least cloth. In Shimizu's advanced robotic system for high-rise building construction, precut and preassembled materials are computer-controlled and delivered on a just-in-time basis to the job site, eliminating on-site storage, with its associated pilferage, damage, and weather loss, and reducing packaging and construction waste by up to 70 percent.[39] The Swedish construction firm Skanska has a similar system for not delivering to the construction site anything that won't go into the building — thus saving not only materials waste but also, importantly, transportation in both directions.

A further key way to waste fewer materials is to improve production quality. The U.S. metal-casting industry[40] has only a 55 percent average yield; 45 percent of its castings are defective and must be melted down and recast. Nearly half the equipment, labor, and melting energy is thus wasted. However, available innovations could probably push yields to 80–90 percent, nearly doubling this industry's output per unit of capital, labor, and energy and cutting its waste of materials by two- to fourfold.[41]

Still another way to save materials is to make a given unit of product more *effective* in providing the desired service. In 1810, iron boilers for locomotives weighed 2,200 pounds per horsepower. Steel boilers cut this ratio by more than threefold by the mid-1800s. By 1900, it was 220 lb/hp; by 1950, with electric locomotives, about 55; and by 1980, with more advanced magnetic materials, about 31.[42] Much of this 71-fold increase in the mass-effectiveness of the iron came from the process change from steam to electric traction.

Other examples of substituting quality and innovation for mass abound in modern life. In the United States, aluminum cans weigh 40 percent less than they did a decade ago;[43] Anheuser-Busch just saved 21 million pounds of metal a year by making its beer-can rims an eighth of an inch smaller in diameter without reducing the contents.[44] A new Dow process that eliminates varnishing, spraying, and baking can save 99.7 percent of the wasted materials and 62 percent of the energy needed for preparing aluminum beverage cans for filling. The mass of the average European yogurt container dropped by 67 percent during the years 1960–90, that of a beer bottle by 28 percent during the years 1970–90, that of a Kodak film canister by 22 percent.[45] An office building that needed 100,000 tons of steel 30 years ago can now be built with no more than 35,000 tons because of better steel and smarter design.[46]

Interface's reduced-face-weight carpet, with lower pile height and higher density, is beautiful, *more* durable, and saves twice as much embodied energy as is needed to run the factory that makes it.[47]

Following its philosophy, stated with emphasis, that "sustainable growth has to be focused on a *functionality* not a product," and that "*the next major step toward sustainable growth is to improve the value of our products and services per unit of natural resources employed*" — that is, to raise resource productivity across the board[48] — DuPont is "downgauging" its polyester film. Making it thinner, stronger, and more valuable lets the company "sell less material at a higher price. On average, for every 10 percent of material reduced there is a 10 percent increase in value and price." Says DuPont, "Our ability to continually improve the inherent properties enables this process to go on indefinitely."[49] The next step is to recycle used film and other polyester products by "unzipping" their molecules. A 100 million-pound-a-year methanolysis plant for this purpose is now being developed in order "to keep those molecules working indefinitely, reducing the need for new feedstocks from natural resources." The same loop-closing process is under way in the carpet industry, whose products, 95 percent petrochemical-based, are now ending up in American landfills at the rate of nearly 10 million pounds a day.[50]

Still another way to save materials is to improve the design not merely of the specific component but of the entire product or process that uses them — the essence of the design approach the designer Buckminster Fuller called "ephemeralization,"[51] doing the job with the merest wisps of material, optimally deployed. In J. Baldwin's words, "The less material used per function, the closer the design is to pure principle." Even less than Fulleresque versions can yield impressive results. For example, a Romanian-American engineer noticed that overhead cranes, a ubiquitous means of moving heavy objects around factories and dockyards, were made of very heavy-duty steel beams. This was necessary because the hoist-motor traveled along the whole length of the cross beam, so when it was in the middle, its great weight would buckle any but the stiffest beam. He redesigned the crane so the hoisting motor was at the end of the cross beam, where its force would be borne straight down the support frame or wall to the ground. A light pulley, not a heavy motor, moved along the cross beam to do the lifting. Result: same lifting capacity, six-sevenths less steel.

BORN-AGAIN MATERIALS

Ultimately, though, people get tired of even a well-designed and efficiently made object, or it gets irreparably destroyed or worn out. Repair, reuse, upgrading, remanufacturing, and recycling are then the five main ways to keep the gift of good materials and good work moving on to other users and other uses. Repair, which works better if the product was designed to facilitate it, returns failed goods to satisfactory service for the same or a thriftier owner. Reuse passes them to another user, or perhaps to a new life with a different purpose.

Industry is already rising to these opportunities. Remanufacturing worldwide is saving energy equivalent to the output of five giant power stations, and saving annually enough raw materials to fill a freight train 1,100 miles long.[52] More than 73,000 U.S. remanufacturing firms, directly employing 480,000 people, generated 1996 revenues of $53 billion, "a value greater than the entire consumer durables industry (appliances, furniture, audio and video, farm and garden equipment)."[53] The biggest remanufacturer in the United States, regularly rebuilding everything from radars to rifles to entire aircraft, is the Department of Defense.[54] The second-biggest U.S. maker of furniture, Herman Miller, has a special daylit factory devoted exclusively to remanufacturing into like-new condition every kind of furniture the company has ever made.[55] Its larger rival, Steelcase, is one of several large firms battling with independent remanufacturers to benefit from remaking its own products.[56]

Big benefits flow to both customers and manufacturers when products get reborn. "Disposable" cameras are affordable because Fuji and Kodak actually salvage them from photo finishers, remanufacture them, reload the film, and sell them again. IBM remanufactures its computers; by 1997 its 100,000-square-foot Asset Recovery Center in Endicott, New York, was recovering 35 million pounds of computers and computer parts per year.[57] The Italian firm Bibo shifted in 1993 from making throwaway plastic plates to charging for their use, then recycling them into new ones.[58] Xerox's worldwide remanufacturing operations boosted earnings by about $200 million over three recent years,[59] $700 million over its whole history; its latest green-designed photocopier, with every part reusable or recyclable, is expected to save it $1 billion via long-term remanufacturing.[60] The University of North Carolina's business school has even hired a professor of "reverse logistics" — "dedistributing" products back from customers for remanufacture.[61]

Obviously, it's much easier to disassemble a product for remanufacturing or reuse of its parts if it was designed with that end in mind. Personal-computer software can now help designers minimize disassembly time and compare the manufacture and disposal impacts of design alternatives.[62] For an increasing range of products in Germany, which pioneered the concept of "extended product responsibility" — you make it, you own it forever — factories producing everything from televisions to cars design them for easy disassembly and disposition, because otherwise the costs of assuming the post-user responsibility are prohibitive. The system, which is spreading across Europe and to Japan, raised the German rate of packaging recycling from 12 percent in 1992 to 86 percent in 1997, and during the years 1991–97, raised plastic collection by 1,790 percent and reduced households' and small businesses' use of packaging by 17 percent.[63] By the end of 1998, some 28 countries had implemented "takeback" laws for packaging, 16 for batteries, and 12 were planning takeback requirements for electronics.[64] Such life-cycle responsibility also creates unexpected benefits: BMW designed the Z-1 sports car's recyclable all-thermoplastic skin to be strippable from the metal chassis in 20 minutes on an "unassembly line" mainly for environmental reasons, but that configuration also made repairs much easier.[65] Or when Alpha-Fry Group in Germany felt burdened by the cleaning costs of returned jars for its solder paste, it switched to pure tin containers, which on return are remelted into new solder — 11 cents cheaper per jar.[66] Avoiding dissipation of materials that are costly to buy and toxic when dispersed is smart business: When Dow announced a $1 billion, 10-year environmental investment program, it was not just being socially responsible. It also anticipated a 30–40 percent annual return.[67]

What if an item's options for repair, reuse, and remanufacturing are exhausted? Then it can be recycled to reconstitute it into another, similar product. As a last resort, it can be downcycled — ground, melted, or dissolved so its basic materials can be reincarnated for a lower purpose, such as a filler material. (Thus do many recycled plastics, no longer pure or strong enough for their original purpose, end up as tent pegs and park benches.) Waste exchanges like the Internet regional exchange sponsored by Canberra (which aims to eliminate waste by 2010), or a private-sector initiative in the region around Brownsville, Texas, and Matamoros, Mexico, aim to match waste materials with potential buyers.[68] Hard-to-recycle materials, like tires, drywall, plastics, insulation, glass, and biosolids, can even be disintegrated by intense sound waves into fine powders for easier reprocessing.[69] Materials that don't now biodegrade can be replaced with compostable ones, like the 1.8 billion potato-starch-and-limestone containers that McDonald's is trying as replacements for polystyrene clamshells — replacements that also happen to cost no more and to need much less energy to make.[70]

These options can shift with improvements in technologies and prices as innovations turn trash into cash. Henry Ford's original car factories had an entire section devoted to reclaiming wooden crates and pallets, many of which were made into autobodies.[71] In 1994, Mitsubishi Motors in Japan, which ships about 2,800 cases of car parts each month to its German distributor, switched from throwaway cardboard and wooden boxes to steel cases that are emptied, folded down, sent back to Japan, reused for an expected ten years, then remanufactured or recycled.[72] Three-fourths of all fresh produce in Germany is now shipped in standard reusable crates sold or leased by the International Fruit Container Organization — another consequence of the 1991 take-back law.[73] DuPont's Petretec process can indefinitely regenerate throwaway polyester film (four-fifths of its billion-dollar films business) into new film with the same quality as that made from virgin materials but costing up to one-fourth less.[74] Recycling old car batteries, which every state requires to be turned in when buying a new one, now provides 93–98 percent of all the lead for U.S. lead-acid batteries.[75]

Some recycled materials, like old bricks, beams, and cobbles, can actually be worth more than new ones. Others can gain novel properties from reprocessing. "Environ" biocomposite, for example, is a decorative nonstructural surface-finish material, made from recycled paper and bioresin, that looks like stone, cuts like wood, is twice as hard as red oak, and has half the weight of granite but better abrasion resistance.[76] When you apply these closed-loop principles to everything from packaging[77] to the three billion tons of construction materials used each year,[78] a substantial amount of reclaiming is at stake — and every ton not extracted, treated, and moved means less harm to natural capital.

What is the potential effect, throughout the industrial system, of combining *all* of these steps — product effectiveness and longevity, minimum-materials design and manufacturing, scrap recovery, reuse, remanufacturing, recycling, and materials savings through better quality, greater product effectiveness, and smarter design? Nobody knows yet. But many experts now believe that if the entire spectrum of materials savings were systematically applied to every material object we make and use, and if enough time were allowed for all the indirect materials savings to work through the structure of the whole economy,[79] together they would reduce the total *flow* of materials needed to sustain a given *stock* of material artifacts or *flow* of services by a factor much nearer to one hundred, or even more, than to ten. This is in large part because smarter design can often wring more service from a given artifact, so all these savings won't just add; they'll multiply. And as each of those multiplying savings turns less green land into brown wasteland, less fossil fuel into climate change, less stuff into waste, it will accelerate the restoration and increase the abundance of natural capital.

In short, the whole concept of industry's dependence on ever faster once-through flow of materials from depletion to pollution is turning from a hallmark of progress into a nagging signal of uncompetitiveness. It's dismaying enough that, compared with their theoretical potential,[80] even the most energy-efficient countries are only a few percent energy-efficient. It's even worse that only one percent of the total North American materials flow ends up in, and is still being used within, products six months after their sale. That roughly one percent materials efficiency is looking more and more like a vast business opportunity. But this opportunity extends far beyond just recycling bottles and paper, for it involves nothing less than the fundamental redesign of industrial production and the myriad uses for its products. The next business frontier is rethinking everything we consume: what it does, where it comes from, where it goes, and how we can keep on getting its service from a net flow of very nearly nothing at all — but ideas.