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Dematerialization

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Until recently the role of consumption as a driving force for environmental change has not been widely explored. This may be due in part to the difficulty of collecting suitable data. This paper approaches the consumption of materials from the perspective of the forces for materialization or dematerialization of industrial products beyond the underlying and obviously very powerful forces of economic and population growth. This examination can occur on both the unit and the aggregate level of materials consumption. Such study may make it possible to assess current streams of materials use and, based on environmental implications, may suggest directions for future materials policy.

The word *dematerialization* is often broadly used to characterize the decline over time in weight of the materials used in industrial end products. One may also speak of dematerialization in terms of the decline in "embedded energy" in industrial products. Colombo [1] has speculated that dematerialization is the logical outcome of an advanced economy in which material needs are substantially satiated.[1] Williams et al. [2] have explored relationships between materials use and affluence in the United States. Perhaps

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[1]In an essay published in the proceedings of the Sixth Convocation of the Council of Academies of Engineering and Technological Sciences, Colombo ([1], pp. 26–27) makes the following observation:

> [E]ach successive increment in per capita income is linked to an ever-smaller rise in quantities of raw materials and energy used. According to estimates by the International Monetary Fund, the amount of industrial raw materials needed for one unit of industrial production is now no more than two-fifths of what it was in 1900, and this decline is accelerating. Thus, Japan, for example, in 1984 consumed only 60 percent of the raw materials required for the same volume of industrial output in 1973.
>
> One reason for this phenomenon is basically twofold. Increases in consumption tend to be concentrated on goods that have a high degree of value added, goods that contain a great deal of technology and design rather than raw materials, and nonmaterial goods such as tourism, leisure activities, and financial services. In addition, today's technology is developing products whose performance in fulfilling desired functions is reaching unprecedented levels. . . . One kilogram of uranium can produce the same amount of energy as 13 U.S. tons of oil or 19 U.S. tons of coal, and in telecommunications 1 ton of copper wire can now be replaced by a mere 25 or so kilograms of fiberglass cable, which can be produced with only 5% of the energy needed to produce the copper wire it replaces.

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we should first ask the question: Is dematerialization taking place? The answer depends, above all, on how dematerialization is defined. The question is particularly of interest from an environmental point of view since the use of less material could translate into smaller quantities of waste generated at both the production and consumption phases of the economic process.

But 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 be produced, and the net result could be a greater amount of waste generated in both production and consumption. From an environmental viewpoint, therefore, *(de)materialization should perhaps be defined as the change in the amount of waste generated per unit of industrial products*. On the basis of such a definition, and taking into account overall production and consumption, we have attempted to examine the question of whether dematerialization is occurring. Our goal is not to answer definitively the question of whether society is dematerializing but rather to establish a framework for analysis to address this overall question and to indicate some of the interesting and useful directions for study. We have examined a number of examples even though the data are not complete.

Undoubtedly, many industrial products have become lighter and smaller with time. Cars, dwelling units, television sets, clothes-pressing irons, and calculators are but a few examples. There is, of course, usually a lower bound regarding how small objects such as appliances can be made and still be compatible with the physical dimensions and limitations of human beings (who are themselves becoming larger), as well as with the tasks to be performed.[2] Apart from such boundary conditions on size and possibly weight of many industrial product units, dematerialization of units of products is perceived to be occurring.

An important question is how far one could drive dematerialization. For example, one might ask, for the automobile, how is real world safety related to its mass? In a recent study [3] Evans has reported that, given a single-car crash, the unbelted driver of a car weighing ~2000 pounds is ~2.6 times as likely to be killed as is the unbelted driver of an ~4000-pound car. The relative disadvantage of the smaller car is essentially the same when the corresponding comparison is made for belted drivers. For two-car crashes it was found that the driver of a 2000-pound car crashing into another 2000-pound car is ~2.0 times as likely to be seriously or fatally injured as is the driver of a 4000-pound car crashing into another 4000-pound car. These results suggest one of the reasons that dematerialization by itself will not be a sufficient criterion for social choice about product design. If the product cannot be practically or safely reduced beyond a certain point, can the service provided by the product be provided in a way that demands less material? To return to the case of transportation, substituting telecommunications for transportation might be a dematerializer, but we have no data on the relative materials demand for the communications infrastructure versus the transportation infrastructure to meet a given need. In any case, demands for communication and transportation appear to increase in tandem, as complementary goods, rather than to substitute for one another.

It is interesting to inquire into dematerialization in the world of miniaturization, not only the world of large objects. In the computer industry, for example, silicon wafers are increasing in size to reduce material losses in cutting. This is understandable consid-

[2]It would be interesting to venture calculations about the significance for materialization of the increasing average height and weight of humans themselves, even though this effect is small compared to that of present population growth. The increase directly expands needs for textiles and food, as well as creates pressure for larger vehicles and dwellings.

TABLE 1
Apparent Consumption of Nonrubber Shoes in the United States

Year	Total consumption	
	Millions of pairs	Shoes per capita year
1970	802	3.9
1975	728	3.4
1976	786	3.6
1977	746	3.4
1978	788	3.6
1979	833	3.7
1980	745	3.3
1981	730	3.2
1982	830	3.6
1983	912	3.9
1984	1,018	4.3
1985	1,097	4.6

Source: U.S. Bureau of the Census, 1975–1985.

ering that ~400 acres of silicon wafer material are used per year by IBM Corporation at a cost of ~$100 million per acre. A processed wafer costs ~$800, and the increase in total wafer area per year is 10%–15%. Although silicon wafers do not present a waste disposal problem from the point of view of volume, they are environmentally important in that their manufacture involves the handling of hazardous chemicals. They are also interesting as an example of how the volume produced of an aggressive new technology will tend to grow because of popularity in the market. Moreover, many rather large plastic and metal boxes are required to enclose and keep cool the microchips made with the wafers, even as the world's entire annual chip production might compactly fit inside one 747 jumbo jet. Thus, such new industries may tend to be simultaneously both friends and foes of dematerialization.

The production of smaller and lighter toasters, irons, TV sets, and other devices in some instances may have resulted in lower-quality products and an increased consumer attitude to "replace rather than repair." In these instances, the number of units produced may have increased. Although dematerialization may be the case on a per-unit basis, the increasing number of units produced may cause an overall materialization trend with time. As an example, the apparent consumption of shoes, which seem increasingly difficult to repair, has risen markedly in the United States since the 1970s, with ~1.1 billion pairs of nonrubber shoes purchased in 1985, compared with ~730 million pairs as recently as in 1981 (Table 1).

In contrast, improvements in quality generally result in dematerialization, as has been the case for tires. The total tire production in the United States has risen over time (Figure 1), following from general increases in both the number of registered vehicles and the total miles of travel have generally increased. However, the number of tires per million miles of travel has declined (Figure 2). Such a decline in tire wear can be attributed to improved tire quality, which results directly in a decrease in the quantity of solid waste due to discarded tires. For example, it is estimated that a tire designed to have a service life of 100,000 miles could reduce solid waste from tires by 60%–75% [4]. Other effective tire waste reduction strategies include tire retreading and recycling, as well as the use of discarded tires as vulcanized rubber particles in roadway asphalt mixes.

Dematerialization of unit products affects, and is influenced by, a number of factors besides product quality. These include ease of manufacturing, production cost, size and

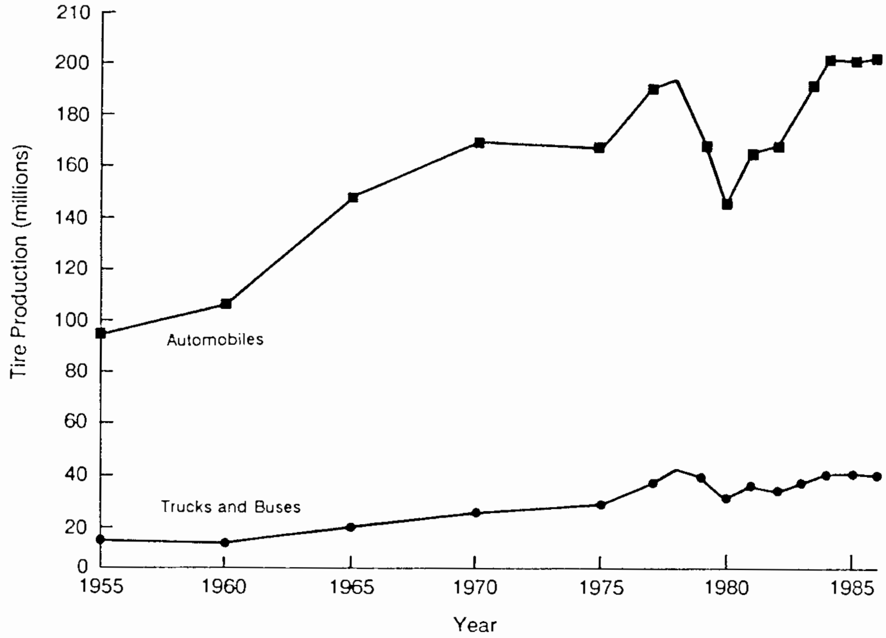

Fig. 1. Production of automobile, truck, and bus tires in the United States. Source: U.S. Bureau of the Census, 1975–1985. Note: Lines connecting data points are for clarity only.

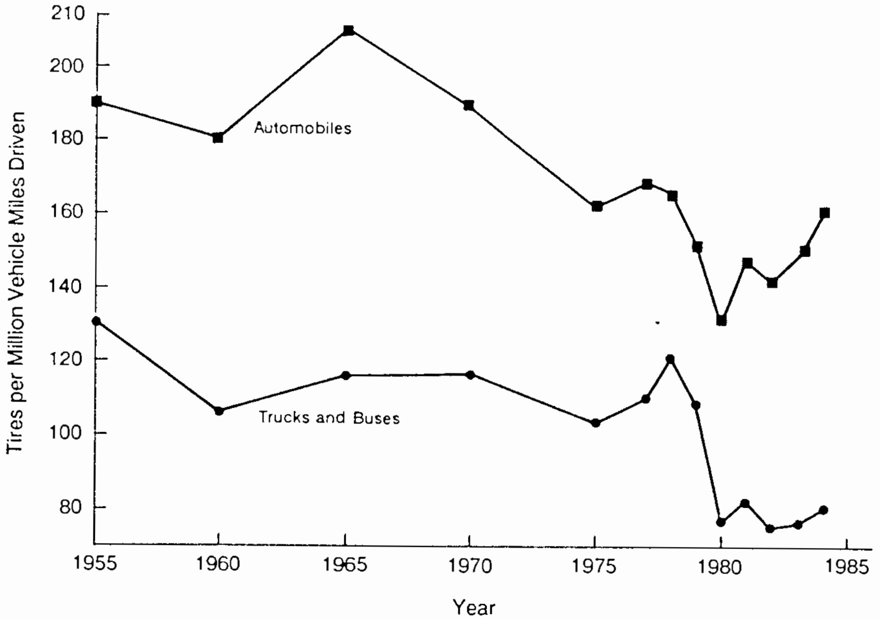

Fig. 2. Consumption of automobile, truck, and bus tires in the United States per million vehicle-miles driven. Source: U.S. Bureau of the Census, 1975–1985. Note: Lines connecting data points are for clarity only.

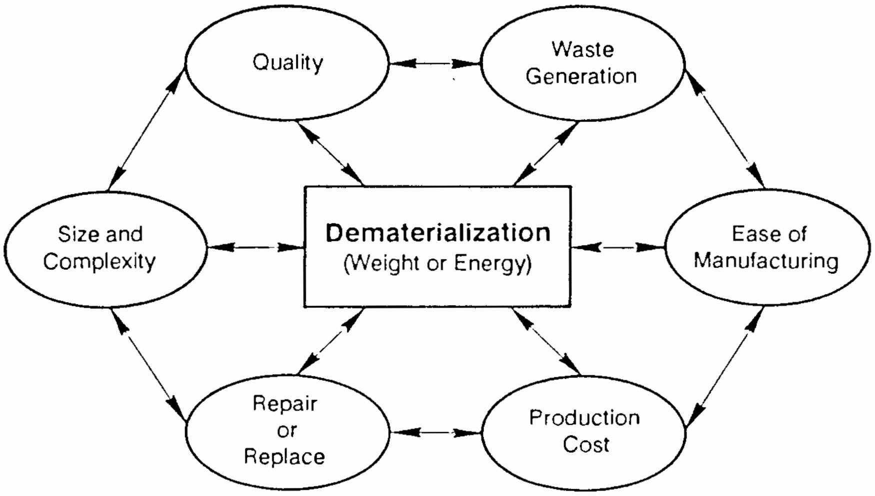

Fig. 3. Factors affecting, and affected by, the dematerialization process. Economic and population growth, of course, also strongly interact with many of the factors.

complexity of the product, whether the product is to be repaired or replaced, and the amount of waste to be generated and processed. These factors influence one another as well (Figure 3). For example, the ease of manufacture of a particular product in smaller and lighter units may result in lower production cost and cheaper products of lower quality, which will be replaced rather than repaired on breaking down. Although a smaller amount of waste will be generated on a per unit basis, more units will be produced and disposed, and there may be an overall increase in waste generation at both the production and consumption ends.

Another factor of interest on the production end is scale. One would expect that so-called economies of scale in production would lead to a set of facilities that embody less material for a given output. Does having fewer, larger plants in fact involve significantly less use of material (or space) than more, smaller ones? At the level of the industrial product, the shift from mainframe computers to personal computers, driven by desires for local independence and convenience, may also be in the direction of materialization.

Among socioeconomic factors influencing society's demand for materials is the nature of various activities, the work force composition, and income levels. For example, as a predominantly agricultural society evolves toward industrialization, demand for materials increases, whereas the transition from an industrial to a service society might bring about a decline in the use of materials. Within a given culture, to what extent are materials use and waste generation an increasing function of income?

The spatial dispersion of population is a potential materializer. Migration from urban to suburban areas, often driven by affluence, requires more roads, more single unit dwellings, and more automobiles with a consequent significant expansion in the use of materials. The movement from large, extended families sharing one dwelling to smaller, nuclear families may be regarded as a materializer if every household unit occupies a separate dwelling. Factors such as photocopying, photography, advertising, poor quality, high cost of repair, and wealth, in general force materialization. Technological innovation, especially product innovation, may also tend to force materialization, at least in the short run. For example, microwave ovens, which are smaller than old-fashioned ovens, have now been acquired by most American households. However, they have come largely as

TABLE 2
Apparent Consumption of Carbon Steel (Million Tons) Products in the United States by End Use, 1970–1982

Year	Motor vehicles	Construction	Consumer durables	Producer durables	Rail transportation	Containers and packaging	Oil and gas industry	Other	Total
1970	19.5	22.9	5.6	11.6	3.4	9.0	1.4	16.8	90.3
1971	23.8	22.7	5.7	11.5	3.4	8.4	1.6	17.7	94.8
1972	24.9	22.3	6.1	12.7	3.1	8.0	1.7	18.7	97.4
1973	29.8	26.4	6.5	14.3	3.4	9.2	2.3	20.9	112.8
1974	24.6	27.7	6.1	14.6	3.8	9.6	2.8	20.9	110.0
1975	19.3	18.3	4.1	10.8	3.3	7.0	3.0	14.8	80.7
1976	26.8	19.0	5.1	12.2	3.2	8.0	2.0	16.0	92.3
1977	28.5	20.1	5.7	12.9	3.6	8.0	3.0	16.8	98.6
1978	27.7	22.5	5.7	14.2	3.7	7.9	3.2	20.3	105.4
1979	22.0	23.0	5.8	14.2	4.3	8.0	3.0	21.9	102.2
1980	14.5	18.9	4.5	11.7	3.3	6.7	4.1	21.4	85.1
1981	15.8	19.2	4.8	12.2	3.2	6.5	5.1	24.9	91.7
1982	10.6	14.7	4.0	8.4	3.0	5.1	3.1	20.7	69.6

These data were constructed by aggregating various American Iron and Steel Institute categories and by allocating ship centers and imports to the end-use sectors.
Source: National Academy of Engineering, 1985.

an addition to, not a substitute for, previous cooking appliances. In the long term, if microwave ovens truly replace older ovens, this innovation may come to be regarded as a dematerializer. National security and war, styles and fashion, and fads may also function as materializers by accelerating production and consumption. Demand for health and fitness, local mobility, and travel may spur materialization in other ways.

The societal driving forces behind dematerialization are, at best, diverse and contradictory. However, the result may indeed be a clear trend in materialization or dematerialization. This could be determined only through collection and analysis of data on the use of basic materials with time, particularly for industry and especially for products with the greatest demand for materials. Basic materials such as metals and alloys (e.g., steel, copper, aluminum), cement, sand, gravel, wood, paper, glass, ceramics, and rubber are among the materials that should be considered. The major products and associated industries that would be interesting to study could well include roads, buildings, automobiles, appliances, pipes (metal, clay, plastic), wires, clothing, newsprint and books, packaging materials, pottery, canned food, and bottled and canned drinks.

Hibbard [5] reported without much detail that per capita intensity of materials use in the United States remained nearly constant between 1974 and 1985 at ~20,000 pounds per capita. It would be useful to confirm this finding and extend the data to explore to what extent such a fact might result from changes in GNP, materials substitutions, market saturation, or other factors of the kind mentioned above. About two-thirds of Hibbard's estimate comes from stone, and from sand and gravel for concrete. These materials may be of less importance for environmental quality than others that are more active in our "industrial metabolism" [6]. Further thought needs to be given to defining baskets of materials whose use over time might form the most meaningful indicators with respect to environment from the point of view of processing and disposal.

Table 2 shows the consumption of carbon steel as a function of time across various major end products. As can be seen, the use of steel in two major industrial activities, namely, construction and automobile manufacture, clearly has been in decline. This

TABLE 3
Pounds of Material (Estimated) in a Typical U.S. Car

Material	1978	1984	1986	1988
Plain carbon steel	1,915.0	1,526.0	1,470.0	1,440.0
High-strength steel	133.0	210.0	223.5	232.0
Stainless steel	26.0	28.5	30.5	31.0
Other steels	55.0	54.0	55.5	45.0
Iron	512.0	481.0	465.5	457.0
Plastics/plastic composites	180.0	204.0	216.0	223.0
Fluids & lubricants	198.0	189.0	181.0	178.0
Rubber	146.5	138.0	134.5	134.0
Aluminum	112.5	136.5	139.5	149.0
Glass	86.5	85.5	85.5	85.0
Copper fabrications and electrical components	37.0	43.5	46.0	49.0
Zinc die castings	31.0	17.5	18.0	19.5
Other materials	137.0	118.5	105.0	124.5
Total	3,569.5	3,232.0	3,170.5	3,167.0

Estimates are based on U.S. models only, including family vans and wagons.
Source: Stark, 1988, pp. 33–37.

significant dematerialization trend has come about by virtue of the use of lightweight, high strength alloys, and synthetics as a substitute for steel and cast iron. The trend is especially evident in the automobile industry where large weight reductions have been achieved by materials substitution in the 1970s in order to reduce the size and weight for energy conservation. Table 3, the estimated pounds of materials used in a typical U.S. manufactured car, shows that the use of plain carbon steel has declined by 475 pounds per car in the 10-year period examined, 1978–1988. On the other hand, the use of high-strength steel, plastic composites, and aluminum has increased by 99, 43, and 36.5 pounds, respectively, in the same period. The result has been a total reduction in weight of a typical U.S. car of ~400 pounds from 1978 to 1988. In the construction industry, however, caution must be exercised in associating the decline in steel use with dematerialization, as such a decline could be indicative of increased popularity for aesthetic, technical, or cost reasons of concrete over steel as the basic construction material.

Growth in the use of advanced materials is expected to continue. For example, it is anticipated that by 1997 the world market for fabricated advanced polymer composites will be almost triple its 1987 level ([7], pp. 57–59). These changes will significantly affect the industries producing conventional materials, as the automotive industry has traditionally been a major consumer of these materials. In 1978, for example, the automotive industry used 22% of the total U.S. steel consumption and 17% of aluminum consumption ([8], p. 6).

The significant decline in the use of steel in the automobile industry provides strong evidence in support of dematerialization at the production end. An examination of energy consumption in selected national economies between 1973 and 1985 further underscores an industrial trend in efficiency and dematerialization (Table 4). Although total energy consumption in most countries has increased considerably during this period, the energy consumed per 1980 constant gross national product (GNP) dollar has declined in nine of ten nations examined. This result may be explained in part by energy efficiency in production or an increasing GNP associated with the service sector. Whether increasing

TABLE 4
Energy Intensity of Selected National Economies, 1973–1985

Nation	1973	1979 (megajoules per 1980 dollar of GNP)	1983	1985	Change, 1973–1985 (present)
Australia	21.6	23.0	22.1	20.3	−6
Canada	38.3	38.8	36.5	36.0	−6
Federal Republic of Germany	17.1	16.2	14.0	14.0	−18
Greece[a]	17.1	18.5	18.9	19.8	+16
Italy	18.5	17.1	15.3	14.9	−19
Japan	18.9	16.7	13.5	13.1	−31
Netherlands	19.8	18.9	15.8	16.2	−18
Turkey	28.4	24.2	25.7	25.2	−11
United Kingdom	19.8	18.0	15.8	15.8	−20
United States	35.6	32.9	28.8	27.5	−23

Source: International Energy Agency, 1987.
[a]Energy intensity increased as a result of a move toward energy-intensive industries such as metal processing.

energy efficiency is a net dematerializer is not clear. Often, increasing energy efficiency involves substituting durable capital goods in the form of better or larger amounts of building materials such as insulation. However, further evidence of dematerialization at the production end is provided by data on industrial solid waste generation, showing a significant decline from 1979 to 1982 (Figure 4).

The generation of municipal solid waste, also shown in Figure 4, has been on the increase. Examination of trends in municipal solid waste generation (total and by each component) provides insight into materialization and dematerialization at the consumption end. The data on municipal solid waste generation suggest a trend toward materialization

Fig. 4. Disposal of municipal and industrial solid waste in the United States. Source: U.S. Bureau of the Census, 1975–1985.

TABLE 5
Amount of Paper in the Total Municipal Solid Waste Generated in the United States

Year	Paper wasted (Million tons)	Paper wasted (Pounds per capita day)	Paper recycled (Millions Tons)
1960	29.9	0.91	5.4
1965	37.9	1.07	5.7
1970	40.4	1.08	6.8
1975	42.7	1.08	8.2
1976	49.1	1.24	9.7
1977	50.8	1.27	10.5
1978	53.4	1.32	10.6
1979	55.5	1.35	11.6
1980	54.1	1.30	11.8
1981	55.5	1.32	11.4
1982	52.2	1.23	10.8

Source: U.S. Bureau of the Census, 1975–1985.

at the consumption end. Table 5, for example, shows the total amount of paper waste in the municipal solid waste in the United States. As can be seen, from 1960 to 1982 there has been an ~75% increase in the total paper waste generated, as well as an ~35% increase in the per capita paper disposed. Such increases are to be viewed in light of predictions that the advent of computers would reduce the use and wastage of paper. A possible contribution of this rise in paper waste is the increase in circulation of daily newspapers from a total of 53.8 million in 1950 to 62.8 million in 1985 [9].

However, other factors must be taken into account, such as changes in the average size and number of pages of newspapers over the country, as well as the amount of waste paper that is used by the industry for printing of new newspapers. Waste paper consumption in the newspaper industry rose from ~2.6 million short tons in 1977 to ~3.6 million short tons in 1987 ([10], p. 22).

Recently, there has been a great deal of interest in the paradox associated with the proliferation of paper in our sociotechnical culture. The following discussion on this point is based on a recent article by E. Tenner [11]. We were all encouraged in the past to believe that information technology as a by-product was going to reduce the consumption of paper significantly. As we all now know, the reverse has transpired, with paper prices rising and trees in jeopardy. Consumption in the United States of writing and printing paper from 1959 to 1986 has increased from ~7 to 22 million tons, and in the short period from 1981 to 1984 the U.S. business use of paper went from 850 billion to 1.4 trillion pages. It is estimated that, between 1986 and 1990, printed material may increase from ~2.5 to 4 trillion pages. In 1987, newsprint production was approaching capacity at ~12 million metric tons; and in the Pan Am Building in New York City a newsstand was reported to carry more than 2000 magazines!

Banks have rid us of the savings account pass book, but in its place there is a spate of paper. Consumers have resisted reliance on home computer on-line services. Moreover, attempts by banks not to provide customers canceled checks have failed; in 1985 U.S. banks processed ~45 billion checks. Plastic credit cards generate considerable amounts of paper, as do automated teller machines. The Rush Medical Library used ~188 linear miles of paper in its photocopy machines in the year 1982–83, and the Princeton University computer center used close to 6 million pages of letter sized laser paper in 1986, plus

~4500 cartons of impact printout paper. Harvard's computer printers use more than 22 million pages a year, not counting personal and faculty computers.

The question has been asked regarding what was wrong with the assumption that electronics would substitute for paper. Apparently nobody anticipated that the microchip would catalyze the burgeoning of paper to such an enormous extent. It would appear that the information age technicians might not have understood that there was not a fixed amount of information and that electronic information was not simply a substitute for paper. Computers are storing in greater quantities more kinds of information than ever before in an extremely compact form, and people prefer reading from the printed page compared to the average computer screen, which in order to have excellent resolution must be improved by a factor of ~10. In addition, there is an increase in office workers compared to those in manufacturing jobs, and this shift leads to an increase in precisely the kind of people who generate paper. Note also that it is easy to produce photocopies compared to the old days, when making carbon copies was indeed a great burden.

In 1959 when Xerox introduced its dry copier, a consulting company estimated that no more than 5000 such copiers would be required in the entire United States. The huge mailings today from businesses and various organizations would not be feasible without the backup of the copier and computer. In 1986 businesses in the United States bought 200,000 photocopiers, and this market is expected to increase for some years to come. It is difficult to comprehend that in 1986 ~45 billion pieces of bulk mail alone were handled by the U.S. Post Office. Notwithstanding the popularity of electronic mail, facsimile machines are materializing by the millions and spewing forth even more paper.

One factor that further encourages storage of data on paper is that it is unsafe to assume that electronically stored records will be readable for even a small fraction of the 200- or 300-year lifetime of acid-free paper [12]. Even if the data are imprinted on poor paper, it is always possible to photocopy it and obtain a better copy than the original, before the sulphite sheet crumbles into its acid grave. Evidence of our insecurity about electronic memory is that, although 90% of securities trades now take place through electronic means, they are, as you surmise, backed up by mountains of paper.

So perhaps it is not surprising that in the information era, the trees of the world are at risk. Moreover, it takes the equivalent of ~1500 pounds of petroleum to make a ton of paper [11]. One wonders which will last longer—energy or the trees? And imagine implications for the environment if a cost effective, but nonbiodegradable, plastic substitute for paper were found! Parenthetically, we might add that biotechnology, operating at the genetic level, might be expected to bring about dematerialization to an extent even beyond what was expected for the information technologies. However, if the end result is not only a new gene but also an enormous "supercow," then the effect again may well be materialization.

The increase in paper waste is closely related to the broad arena of efficiency in use as well as recycling. Examination of municipal and industrial waste (solid and liquid) shows the annual generation rate in pounds per capita in the United States was estimated in the mid-1970s at ~3600 [13]. Japan was closest to the United States with an estimated average of 800, followed by the Netherlands at 680 and the Federal Republic of Germany at 500. We are uncertain of the reliability and comparability of the estimates, as Cointreau [14], for example, shows only a factor of two difference in daily per capita waste generation between New York and such cities as Hamburg and Hong Kong. Moreover, comparable estimates that we are aware of include emissions of environmentally important substances such as gaseous air pollutants or carbon dioxide. The human race now annually discharges to the atmosphere more than 5 billion tons of carbon dioxide, or 1 ton per person.

TABLE 6
Scrap Use in the United States

Material	Total consumption (million short tons)			Percent of total consumption in recycled scrap		
	1977	1982	1987	1977	1982	1987
Aluminum	6.49	5.94	6.90	24.1	33.3	29.6
Copper	2.95	2.64	3.15	39.2	48.0	39.9
Lead	1.58	1.22	1.27	44.4	47.0	54.6
Nickel	0.75	0.89	1.42	55.9	45.4	45.4
Steel/iron	142.40	84.00	99.50	29.4	33.4	46.5
Zinc	1.10	0.78	1.05	20.9	24.1	17.7
Paper	60.00	61.00	76.20	24.3	24.5	25.8

Source: Institute of Scrap Recycling Industries, 1988.

The considerably smaller rates of waste generation in other industrial countries are often attributed to either a lower consumption rate of goods or a more serious effort to recover and reuse the wastes [13]. In this connection, it would be instructive to examine questions such as how much paper per capita is sold in the United States, what fraction of a newspaper is recovered, can more envelopes be designed to be reused, what fraction of paper wasted is still usable, and what fraction of paper available for recycling is actually recycled. According to one estimate [15], only 24% of the 47 million short tons of the recyclable paper in the U.S. solid waste was recovered in the early 1970s.

Although paper makes up the greatest fraction of solid waste (30%–35%), it has one of the lowest recovery rates, following textiles (17%) and zinc (14%). These low recovery rates are more than likely due to economic reasons. A recent *Wall Street Journal* article [16] stated, "The bottom has fallen out of the market for recycled newspapers, exacerbating the nation's already critical garbage problems." It is reported that just a few months ago municipalities were receiving as much as $25 per ton for their newspaper waste, while now they have to pay ~$5–$25 per ton to have the old newspapers hauled away. This situation is counter to the myth that recycling should always make money. It has been argued that perceived scarcity of physical resources usually leads to technological substitutions [6,17,18]. If a substitution is not possible, then recycling is considered. From a purely economic standpoint, high-grade resources are exploited before lower grade resources and recycling are considered economically viable.

An overall view of scrap usage in the United States during the years 1977–1987 is shown in Table 6, where data on total consumption and percent of total consumption in recycled material for a number of metals, as well as paper, are presented. Among the metals, there has been an increase in total consumption for aluminum, lead, and nickel over the 10-year period examined, while there has been a decrease for steel and iron, as mentioned earlier. During this same period the percent of total consumption in scrap has increased for aluminum, lead, and steel. Zinc and paper have the lowest percent of total consumption in recycled scrap, namely, 17.7% and 25.8% in 1987, respectively. It is difficult to see exactly what correlations may exist and the underlying reasons for the observed variations. The availability of scrap might be expected to depend on total consumption, but it is also a function of usage, costs, and other factors.

Another question to be raised in connection with the economics of consumption and disposal is what the "true" cost of consumption and processing of the generated waste is to society. What is the true cost of burning fossil fuel for transportation considering, for example, the finiteness of resources and consequent long-term damage to the environment? Should high-grade resources be made available at much higher cost so the profits may be reinvested toward the development of the capital and the knowledge to permit use of lower grade resources and the development of technological substitutes? What is the actual disposal cost of municipal and industrial waste? To what extent is the cost of waste collection subsidized by different societies and different segments of a society? Would a higher cost for garbage collection effectively encourage recycling, sorting recyclable materials at the generation source, and dematerialization? Would it encourage more illegal dumping? Can society truly afford to continue functioning in its present "throw-away" mode of products such as food, clothing, diapers, and shoes, as well as watches, radios, flashlights, light bulbs, cameras, calculators, pens and pencils, razors, knives, spoons, and forks?

A practice potentially very risky to society is the emission of chlorofluorocarbons (CFCs) to the atmosphere [19,20]. Projected depletion of the ozone layer, attributed to the environmental release of CFCs, resulted in the U.S. ban of nonessential CFC aerosol propellants in the mid-1970s. Combined release of CFC-11 and CFC-12 in the United States traditionally accounted for about one-third of the total worldwide release of these substances. The aerosol ban, however, resulted in only a gradual and temporary decline of production and emissions levels [20], because CFC-11 and CFC-12 have had other, growing nonaerosol industrial applications such as in refrigeration, air-conditioning, cleaning electronic and computer equipment, and foam manufacturing [21]. According to a 1987 international treaty, the industrial countries agreed to cut in half the CFC production by the year 2000. In March 1989 a conference in London, attended by over 100 nations, entertained a proposal for the total elimination of CFCs by the year 2000. Although it certainly seems prudent to reduce or eliminate CFC use, one wonders whether their elimination may yet result in further materialization, for example, through a need to have bulkier refrigerators again.

Lead is another example of a substance whose wide use presents a clean up problem. Lead-containing aerosols, paint, and vehicular exhaust are among major sources of lead in the environment. It has been estimated that an effective program to reduce exposure to lead paint from the interiors of the nation's housing stock would cost $28–$35 billion [22]. Although ingestion of lead-based paint chips is regarded as the major cause of lead poisoning in children, lead exposure results from a combination of sources, including automotive lead emissions. It is estimated that 70% of the lead in gasoline is emitted into the atmosphere, and that this accounted for ~90% of airborne lead emissions [23].

In the 1970s the U.S. Environmental Protection Agency (EPA) enacted a phased-reduction schedule for the lead content of gasoline that has resulted in installation of lead-intolerant catalytic converters in virtually all cars produced in the United States. The national average lead content of all grades of gasoline declined from ~2.5 grams per gallon in 1968 to less than 0.1 in 1988, and sales of unleaded gasoline have consistently increased. Lead was introduced as an antiknock additive to gasoline in the 1930s to increase efficiency of automobile engines. As such, lead may have contributed to dematerialization of cars in terms of either weight or energy. But, we did not foresee sufficiently that the increasing quantity of lead in our environment would itself become a serious problem.

In a recent study [24], the EPA identified 31 broad categories of environmental problems and rank ordered the seriousness of these problems according to the risk they posed to the population in terms of total incidence of disease and other factors. The risks considered included cancer risk, noncancer health risks, ecological effects, and welfare effects such as materials damage to industrial, agricultural, commercial, and residential properties, among others. Lead and the CFCs discussed above along with, for example, sulfur dioxide, suspended particulates, carbon monoxide, nitrogen oxides, and sulfuric acid were included in three air pollutant categories regarded as having relatively high risks. Industrial dematerialization would have a significant impact on the reduction of the various risks associated with the above air pollutants.

Other problems evaluated in the EPA report, in which materialization is a central factor, included nonhazardous municipal and industrial waste, as well as mine waste. Discharges of direct and indirect effluents and municipal sludge into surface waters and wetlands were also among high-risk problems that we might associate with materialization. In this connection, discharges of sludge and medical waste into the oceans are pressing problems with high news visibility.

During the past few years, the Atlantic Ocean has been regurgitating progressively more garbage and waste onto the beaches of the northeastern United States, especially around New York and New Jersey. Included in the dumping that causes this shocking situation are ~500,000 pounds per week of medical waste out of New York City alone. Examples of materialization resulting from medical technology are the plastic throw away hypodermic syringe and throw away needles. In the old days glass syringes and high-quality surgical steel needles were sterilized and used many times over. At the present time, syringes, for many good reasons, are used but once and thrown away, as is much other medical material.

With the burgeoning of hazardous medical waste, the disposal task, especially at hospitals, becomes complex and expensive. This unquestionably leads to illegal dumping for the purposes of cutting cost and avoiding demanding procedures. It is difficult to believe that clinic and hospital authorities are not aware of the dangers associated with illegal disposal. The midnight dumping of medical wastes raises the question of the role of the entire spectrum of "criminal" activity in our society with regard to transport and disposal of materials. Attempts are being made to determine at what point in the disposal chain the system breaks down. The solution to this type of complex problem must, of necessity, have an ethical component, with better values placed over and above such consideration as cost-effectiveness.

Although no recycling process is 100% efficient, recycling is a promising means of dematerialization. The construction industry is one of the major generators of solid waste. What fraction of construction waste is reusable? To what extent are brick, wood, steel, and asphalt reused? In general, a more thorough examination of practice in the construction industry regarding waste generation and processing is warranted in studies of dematerialization. How much waste is generated in construction activities such as paving roads, and building houses? What happens to the waste from building construction or from demolished buildings? What determines whether a building should be demolished or renovated? What fraction of buildings are demolished as a result of safety considerations or to be replaced by a larger structure for economic reasons? What is the potential for recycling materials resulting from demolition operations, as well as various construction activities? To what extent do construction and demolition "activate" environmentally significant materials? The embalming of no-longer-usable nuclear power plants is an interesting case of permanent structural materialization.

In a recent essay [25], Marland and Weinberg make a powerful case for a life cycle approach to infrastructure systems, exploring connections between quality of service provided and aging of facilities. They ask three fundamental questions about a variety of infrastructure systems: What actually is the characteristic longevity of a given infrastructure? How long could it last? How long should it last? The first attempt at a demography of infrastructure needs to be pursued in many areas in connection with materialization. From an environmental perspective, what could and should be the design life of everything we create? In the area of nuclear materials we are accustomed to asking long-range questions about how materials will be transported, stored, and disposed of. Such a life cycle perspective might be usefully applied to other materials as we contemplate transforming them for human purposes, and thus provide guidance about instances in which dematerialization rather than materialization should be our eventual objective. More generally, materialization impact assessments might be useful to undertake for selected new products and activities.

The questions raised and discussions set forth in this essay point toward a number of overall objectives, namely, to single out the important driving forces behind trends in materialization and dematerialization, to determine whether on a collective basis such forces drive society toward materialization or dematerialization, and to assess the environmental implications of these long-term trends. Many questions remain to be answered quantitatively; for example, how much basic material and how many of each major product are used per capita over time and what is the lifetime of various manufactured products? Considering that for every person in the United States we mobilize 10 tons of materials and create a few tons of waste per year, it is clearly important to gain a better understanding of the potential forces for dematerialization. Such understanding is essential for devising strategies to maintain and enhance environmental quality, especially in a nation and a world where population and the desire for economic growth are ever increasing.

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References

1. Colombo, U., The Technology Revolution and the Restructuring of the Global Economy, *Globalization of Technology: International Perspectives*, in J. H. Muroyama and H. G. Stever, eds., National Academy Press, Washington, D.C., 1988, pp. 23–31.
2. Williams, R. H., Larson, E. D., and Ross, M. H. Materials, Affluence, and Industrial Use, *The Annual Review of Energy* 12, 99–144 (1987).
3. Evans, L., Car Size and Safety: Results from Analyzing U.S. Accident Data, in *Proceedings of the Tenth International Conference on Experimental Safety Vehicles, Oxford, U.K.*, July 1–5, 548–555 (1985).
4. Westerman, R. R., Tires: Decreasing Solid Wastes and Manufacturing Throughput, Report EPA-600/5-78-009, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.
5. Hibbard, W. R., Metals Demand in the United States: An Overview, *Materials and Society* 10(3), 251–258 (1986).
6. Ayres, R. U., Industrial Metabolism, in *Technology and Environment*, J. H. Ausubel and H. E. Sladovich, eds., National Academy Press, Washington, D.C., 1989.
7. Miller, E., ed., *Ward's Auto World*, Wards Communications, Inc., Detroit, Michigan, 1988.
8. Motor Vehicle Manufacturers Association, *Information on the Use of Various Materials in the Automotive Industry*, Policy Analysis Department, MVMA, Detroit, Michigan, 1982.
9. U.S. Bureau of the Census, *Statistical Abstract of the United States*, U.S. Government Printing Office, Washington, D.C., 1975–1985.
10. Institute of Scrap Recycling Industries. *Facts—1987 Yearbook*. ISRI, Washington, D.C., 1988.
11. Tenner, E., The Paradoxical Proliferation of Paper, *Princeton Alumni Weekly*, March 9, 1988.
12. National Research Council, *Preservation of Historical Records*, Commission on Engineering and Technical Systems, National Academy Press, Washington, D.C., 1986.
13. Tchobanoglous, G., Theisen, G. H., and Eliassen, R. E., *Solid Wastes—Engineering Principles and Management Issues*, McGraw Hill, New York, 1977.

14. Cointreau, S. J., *Environmental Management of Urban Solid Wastes in Developing Countries*, World Bank, Washington, D.C., 1982.
15. Hagerty, D. J., Pavoni, J. L., and Heer, J. E. Solid Waste Management, in *Environmental Engineering Series*, Van Nostrand Reinhold, New York, 1973.
16. Paul, B., Market for Recycled Newspapers in U.S. Collapses, Adding to Solid Waste Woes, *Wall Street Journal*, January 25, 1989, p. B4(E).
17. Ausubel, J. H., Regularities in Technological Development: An Environmental View, in *Technology and Environment*, J. H. Ausubel and E. Sladovich, eds, National Academy Press, Washington, D.C., 1989.
18. Lee, T. H., Advanced Fossil Fuel Systems and Beyond, in *Technology and Environment*, J. H. Ausubel and E. Sladovich, eds, National Academy Press, Washington, D.C., 1989.
19. Friedlander, S. K., Environmental Issue: Implications for Engineering Design and Education, in *Technology and Environment*, J. H. Ausubel and E. Sladovich, eds, National Academy Press, Washington, D.C., 1989.
20. Glas, J. P., Protecting the Ozone Layer. A Perspective from Industry, in *Technology and Environment*, J. H. Ausubel and E. Sladovich, eds, National Academy Press, Washington, D.C., 1989.
21. Warhit, E., Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production, Report EPA-560/12-80-0016, U.S. Environmental Protection Agency, Washington, D.C., 1980.
22. Chapman, E. R., and Kowalski, J. G., Lead Paint Abatement Costs: Some Technical and Theoretical Considerations, U.S. Department of Commerce, Washington, D.C., 1979.
23. Boggess, W. R., and Wixson, B. G., Lead in The Environment, Report NSF/RA-770214, Washington, D.C., National Science Foundation, 1977.
24. International Energy Agency (IEA), *Energy Conservation in IEA Countries*, Organization for Economic Cooperation and Development and IEA, Paris, 1987.
25. Marland, G., and Weinberg, A. M., Longevity of Infrastructure, in *Cities and Their Vital Systems*, J. H. Ausubel and R. Herman, eds., National Academy Press, Washington, D.C., 1988, pp. 312–332.
26. National Academy of Engineering, *The Competitive Status of the U.S. Steel Industry, Steel Panel Committee on Technology and International Economic and Trade Issues*, National Academy Press, Washington, D.C., 1985.
27. Stark, H. A., ed., *Ward's Automotive Yearbook*, Wards Communications, Inc., Detroit, Michigan, 1988.
28. U.S. Environmental Protection Agency, *Unfinished Business: A Comparative Assessment of Environmental Problems*, National Technical Information Services, Springfield, Virginia, 1988.