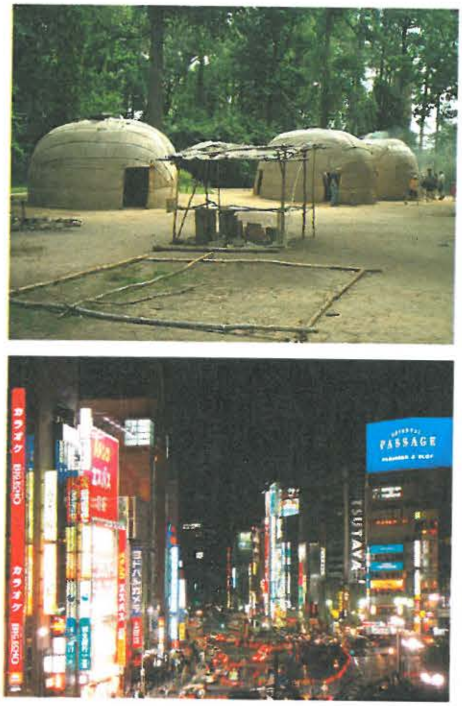
CHAPTER 1

Introduction: material dependence



Renewable and non-renewable construction. Above: Indian village reconstruction. (Image courtesy of Kevin Hampton http://www.wm.edu/niahd/journals). Below: Tokyo at night. (Image courtesy of http://www.photoeverywhere.co.uk index).

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1.1 Introduction and synopsis

This book is about *materials and the environment*: the eco-aspects of their production, their use, and their disposal at end of life. It is also about ways to choose and design with them in ways that minimize the impact they have on the environment. Environmental harm caused by industrialization is not new. The manufacturing midlands of 18th century England acquired the name "Black Country" with good reason; and to evoke the atmosphere of 19th century London, Sherlock Holmes movies show scenes of fog—known as "pea-soupers"—swirling round the gas lamps of Baker Street. These were localized problems that have, today, largely been corrected. The

Materials and the Environment.

change now is that some aspects of industrialization have begun to influence the environment on a global scale. Materials are implicated in this. As responsible materials engineers and scientists, we should try to understand the nature of the problem—it is not simple—and to explore what, constructively, can be done about it.

This chapter introduces the key role materials have played in advancing technology and the dependence—addiction might be a better word—that this has bred. Addictions demand to be fed, and this demand, coupled with the world's continued population growth, consumes resources at an ever-increasing rate. This has not, in the past, limited growth; the earth's resources are, after all, very great. But there is increasing awareness that the limits *do* exist, that we are approaching some of them, and that adapting to them will not be easy.

1.2 Materials: a brief history

Materials have enabled the advance of mankind from its earliest beginnings—indeed the ages of man are named after the dominant material of the day: the *Stone Age*, the *Copper Age*, the *Bronze Age*, the *Iron Age* (Figure 1.1). The tools and weapons of prehistory, 300,000 or more years ago, were bone and stone. Stones could be shaped into tools, particularly flint and quartz, which could be flaked to produce a cutting edge that was harder, sharper, and more durable than any other naturally occurring materials. Simple but remarkably durable structures could be built from the materials of nature: stone and mud bricks for walls; wood for beams; bark, rush, and animal skins for roofing.

Gold, silver, and copper, the only metals that occur in native form, must have been known about from the earliest time, but the realization that they were ductile, that is, that they could be beaten into a complex shape, and, once beaten, become hard, seems to have occurred around 5500 BC. By 4000 BC, there is evidence that technology to melt and cast these metals had developed, allowing for more intricate shapes. Native copper, however, is not abundant. Copper occurs in far greater quantities as the minerals azurite and malachite. By 3500 BC, kiln furnaces, developed for pottery, could reach the temperature and create the atmosphere needed to reduce these minerals, enabling the tools, weapons, and ornaments that we associate with the Copper Age to develop.

But even in the worked state, copper is not all that hard. Poor hardness means poor wear resistance; copper weapons and tools were easily blunted. Sometime around 3000 BC the probably accidental inclusion of a tin-based mineral, cassiterite, in the copper ores provided the next step in technology—the production of the copper-tin alloy *bronze*. Tin gives bronze a hardness that pure copper cannot match, allowing superior tools and weapons to be produced. This discovery of *alloying*—the hardening of one metal by adding another—stimulated such significant technological advances that it, too, became the name of an era: the Bronze Age.

"Obsolescence" sounds like 20th century vocabulary, but the phenomenon is as old as technology itself. The discovery, around 1450 BC, of ways to reduce ferrous

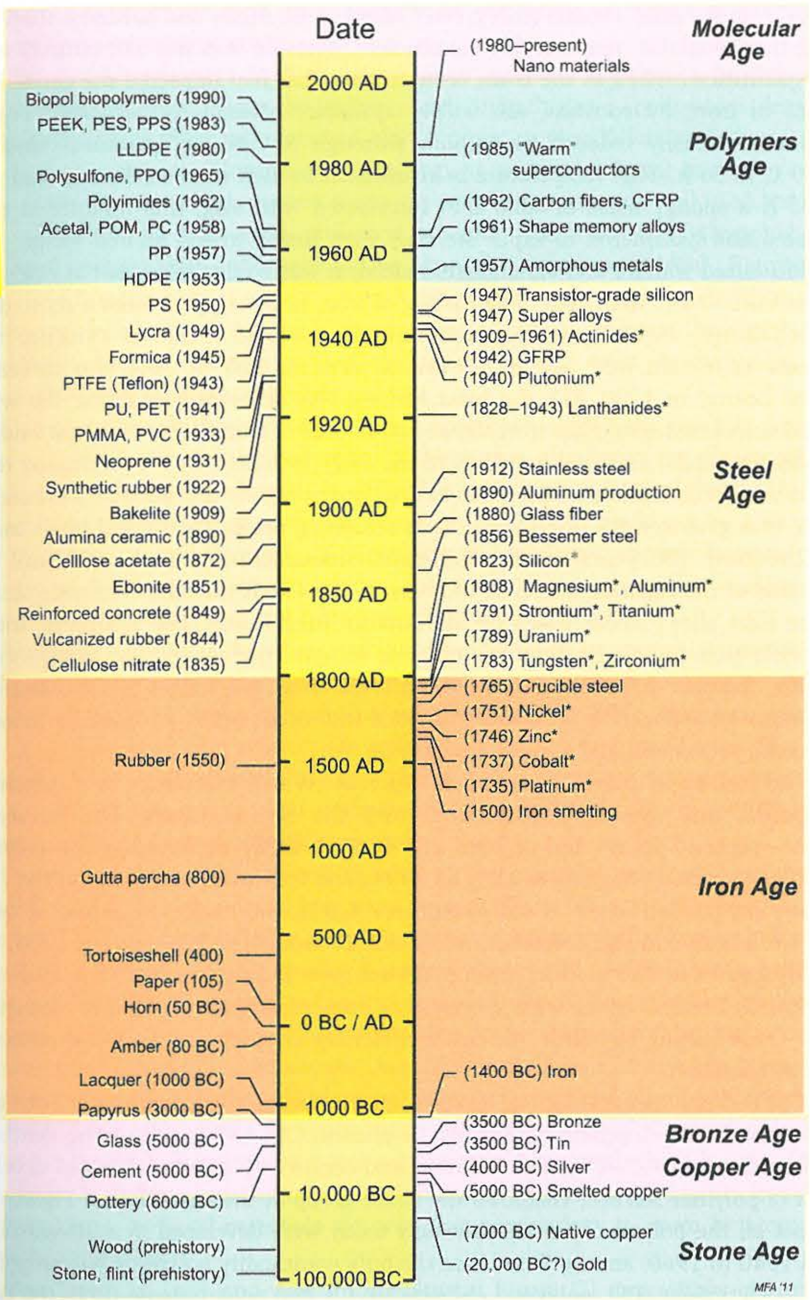

FIGURE 1.1 *The materials timeline. The scale is nonlinear, with big steps at the bottom, small ones at the top. A star (*) indicates the date at which an element was first identified. Unstarred labels give the date at which the material became of practical importance.*

oxides to make iron, a metal with greater stiffness, strength, and hardness than any other then available, rendered bronze obsolete. Metallic iron was not entirely new: tiny quantities existed as the cores of meteorites that had impacted the earth. The oxides of iron, by contrast, are widely available, particularly *hematite*, Fe_2O_3. Hematite is easily reduced by carbon, although it takes temperatures close to 1,100°C to do it. This temperature is insufficient to melt iron, so the material produced is a spongy mass of solid iron intermixed with slag; this mixture is then reheated and hammered to expel the slag, then forged to the desired shape. Iron revolutionized warfare and agriculture; indeed, it was so desirable that at one time it was worth more than gold. The casting of iron, however, presented a more difficult challenge, requiring temperatures around 1,600°C. There is evidence that Chinese craftsmen were able to do this as early as 500 BC, but two millennia passed before, in 1500 AD, the blast furnace was developed, enabling the widespread use of cast iron. Cast iron allowed structures of a new type: the great bridges, railway terminals, and civil buildings of the early 19th century are testimony to it. But it was steel, made possible in industrial quantities by the Bessemer process of 1856, that gave iron the dominant role in structural design that it still holds today. For the next 150 years metals dominated manufacturing. It wasn't until the demands of the expanding aircraft industry in the 1950s that the emphasis shifted to the light alloys (those based on aluminium, magnesium, and titanium) and to materials that could withstand the extreme temperatures of the gas turbine combustion chamber (*super alloys*—heavily alloyed iron- and nickel-based materials). The range of application of metals expanded into other fields, particularly those of chemical, petroleum, and nuclear engineering.

The history of polymers is rather different. Wood, of course, is a polymeric composite, one used in construction from the earliest times. The beauty of amber—petrified resin—and of horn and tortoise shell—made up of the polymer keratin—attracted designers as early as 80 BC and continued to do so into the 19th century (in London, there is still a Horners' Guild, the trade association of those who work horn and shell). Rubber, which wasn't brought to Europe until 1550, was already known of and used in Mexico. Its use grew in importance in the 19th century, partly because of the wide spectrum of properties made possible by vulcanization—cross-linking by sulfur—to create materials as elastic as latex and others as rigid as ebonite.

The real polymer revolution, however, had its beginnings in the early 20th century with the development of Bakelite, a phenolic, in 1909, and of the synthetic butyl rubber in 1922. This was followed mid-century by a period of rapid development of polymer science, visible as the dense group at the upper left of Figure 1.1. Almost all the polymers we use so widely today were developed in a 20-year span from 1940 to 1960; among them were the bulk commodity polymers polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), and polyurethane (PU), the combined annual tonnage of which now approaches that of steel. Designers seized on these new materials—they were cheap, brightly colored, and easily molded to complex shapes—to produce a spectrum of cheerfully ephemeral products. Design with polymers has since matured: they are now as important as metals in household products and automobile engineering.

The use of polymers in high-performance products requires a further step. "Pure" polymers do not have the stiffness and strength these applications demand; to provide it, they must be reinforced with ceramic or glass fillers and fibers, making them *composites*. Composite technology is not new. Straw-reinforced mud brick (adobe) is one of the earliest materials of architecture, one still used today in parts of Africa and Asia. Steel-reinforced concrete—the material of shopping centers, road bridges, and apartment blocks—appeared just before 1850. Reinforcing concrete with steel gave it tensile strength where previously it had none, thus revolutionizing architectural design; it is now used in greater volume than any other man-made material. Reinforcing metals, already strong, took much longer, and even today metal matrix composites are few.

The period in which we now live might have been named the Polymer Age had it not coincided with yet another technical revolution, that based on silicon. Silicon was first identified as an element in 1823, but found few uses until the realization, in 1947, that, when doped with tiny levels of impurity, it could act as a rectifier. This discovery created the fields of electronics and modern computer science, revolutionizing information storage, access and transmission, imaging, sensing and actuation, automation, and real-time process control.

The 20th century saw other striking developments in materials technology. Superconduction, discovered in mercury and lead when cooled to 4.2°K (−269°C) in 1911, remained a scientific curiosity until, in the mid '80s, a complex oxide of barium, lanthanum, and copper was found to be superconducting at 30°K. This triggered a search for superconductors with yet higher transition temperatures, leading, in 1987, to one that worked at the temperature of liquid nitrogen (98°K), making applications practical, though they remain few.

During the early 1990s, scientists realized that material behavior depended on scale, and that the dependence was most evident when the scale was that of nanometers (10^{-9} m). Although the term *nanoscience* is new, technologies that use it are not. The ruby red color of medieval stained glasses and the diachromic behavior of the decorative glaze known as "lustre" derive from gold nanoparticles trapped in the glass matrix. The light alloys of aerospace derive their strength from nanodispersions of intermetallic compounds. Automobile tires have, for years, been reinforced with nanoscale carbon. Modern nanotechnology gained prominence with the discovery that carbon could form stranger structures: spherical C_{60} molecules and rod-like tubes with diameters of a few nanometers. Now, with the advance of analytical tools capable of resolving and manipulating matter at the atomic level, the potential exists to build materials the way that nature does it, atom by atom and molecule by molecule.

If we now step back and view the timeline of Figure 1.1 as a whole, clusters of activity are apparent—there is one in Roman times, one around the end of the 18th century, and one in the mid 20th century. What was it that triggered the clusters? Scientific advance, certainly. The late 18th and early 19th century was the time of the rapid development of inorganic chemistry, particularly electrochemistry, and it was this that allowed new elements to be isolated and identified. The mid 20th century saw the birth of polymer chemistry, spawning the polymers we use today and providing key concepts in unraveling the behavior of the materials of nature. But there may be more to it than that. Conflict stimulates science. The first of these two periods coincides with the Napoleonic Wars (1796–1815), one in which technology, particularly in France, developed rapidly. The second coincided with the Second World War (1939–1945), in which technology played a greater part than in any previous conflict. Defense budgets have, historically, been prime drivers for the development of new materials. One hopes that scientific progress and advances in materials are possible without conflict, and that the competitive drive of free markets can be an equally strong driver of technology. It is interesting to reflect that more than three quarters of all the materials scientists and engineers who have *ever* lived are alive today, and all of them are pursuing better materials and better ways to use them. Of one thing we can be certain: there are many more advances to come.

1.3 Learned dependency: the reliance on nonrenewable materials

Now back to the main point: the environmental aspects of the way we use materials. "Use" is too weak a word—it sounds as if we have a choice: use, or perhaps not use? We don't just "use" materials, we are totally dependent on them. Over time this dependence has progressively changed from a reliance on renewable materials—the way mankind existed for thousands of years—to one that relies on materials that consume resources that cannot be replaced.

As little as 300 years ago human activity subsisted almost entirely on renewables: stone, wood, leather, bone, and natural fibers. The few nonrenewables—iron, copper, tin, zinc—were used in such small quantities that the resources from which they were drawn were, for practical purposes, inexhaustible. Then, progressively, the nature of the dependence changed (Figure 1.2). Bit by bit, nonrenewables displaced renewables until, by the end of the 20th century, our dependence on them was, as already said, almost total.

Dependence is dangerous; it is a genie in bottle. Take away something on which you depend, meaning that you can't live without it, and life becomes difficult. Dependence exposes you to exploitation. While a resource is plentiful, market forces ensure that its price bears a relationship to the cost of its extraction. But the resources from which many materials are extracted, oil among them, are localized in just a few countries. While these countries compete for buyers, the price remains geared to the cost of production. But if demand exceeds supply or the producing nations reach arrangements to limit it, the genie is out of the bottle. Think, for instance, of the price of oil, which today bears no relationship to the cost of producing it.

Dependence, then, is a condition to be reckoned with. We will encounter its influence in subsequent chapters.

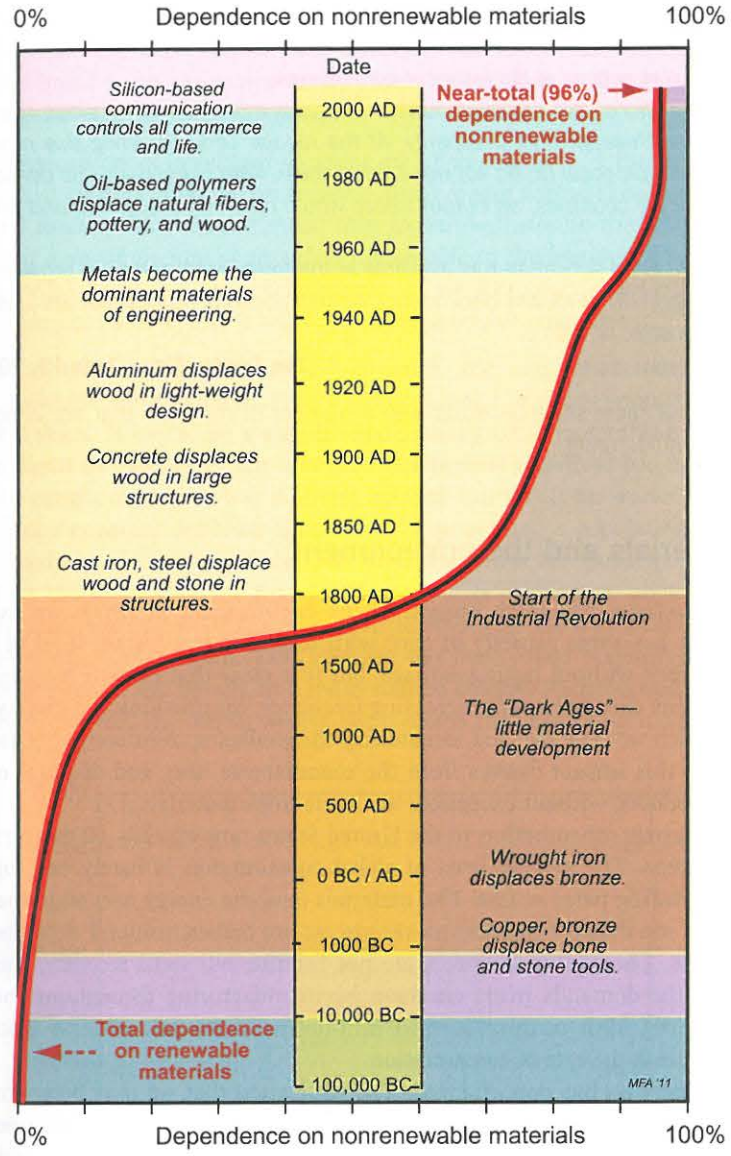

FIGURE 1.2 *The increasing dependence on nonrenewable materials over time, rising to 96% by weight today. This dependence is not of concern when resources are plentiful but is an emerging problem as they become scarce. (Data in part from USGS [2002].)*

News-clip: dangerous dependence

Oil addiction puts us at the mercy of our enemies.

Western nations rely on Saudi Arabia to pump more oil when prices rise to levels that threaten their prosperity. At the regular OPEC meeting this month the Saudi's proposal [to do so] was turned down. With rising domestic demand in producing countries, an output freeze would mean tight supplies and price rises.

There is no substitute fuel available in the foreseeable future to replace oil for transport. That means dependence on regimes in countries that are unstable, or hostile, or both. . . .

***The Sunday Times*, June 19, 2011**

Much the same situation exists with a number of materials that are critical for modern manufacturing.

1.4 Materials and the environment

All human activity has some impact on the environment in which we live. The environment has some capacity to cope with this so that a certain level of impact can be absorbed without lasting damage, but it is clear that current human activities exceed this threshold with increasing frequency, diminishing the quality of the world in which we now live and threatening the wellbeing of future generations. At least part of this impact derives from the manufacture, use, and disposal of products, and products, without exception, are made from materials.

The materials consumption in the United States now exceeds 10 metric ton per person per year. The average level of global consumption is barely one eighth of this but is growing twice as fast. The materials (and the energy needed to make and shape them) are drawn from *natural resources*: ore bodies, mineral deposits, fossil hydrocarbons. The earth's resources are not infinite, but until recently, they have seemed so: the demands made on them by manufacturing throughout the 18th, 19th, and early 20th century seemed infinitesimal, the rate of new discoveries always outpacing the rate of consumption.

This perception has now changed. The realization that we may be approaching certain fundamental limits seems to have surfaced with surprising suddenness, but warnings that things can't go on forever are not new. Thomas Malthus, writing in 1798, foresaw the link between population growth and resource depletion, predicting gloomily that "the power of population is so superior to the power of the earth to produce subsistence for man that premature death must in some shape or other visit the human race." Almost 200 years later, in 1972, a group of scientists known as the Club of Rome reported their modeling of the interaction of population growth, resource depletion, and pollution, concluding that "if (current trends) continue unchanged . . . humanity is destined to reach the natural limits of development within the next 100 years." The report generated both consternation and criticism, largely on the grounds that the modeling was over-simplified and did not allow for scientific and technological advance. But in the last decade, thinking about this broad issue has reawakened. There is a growing acceptance that, in the words of another distinguished report:

> *. . . many aspects of developed societies are approaching . . . saturation, in the sense that things cannot go on growing much longer without reaching fundamental limits. This does not mean that growth will stop in the next decade, but that a declining rate of growth is foreseeable in the lifetime of many people now alive. In a society accustomed . . . to 300 years of growth, this is something quite new, and it will require considerable adjustment.****

The causes of these concerns are complex, but one stands out: population growth. Examine, for a moment, Figure 1.3. It is a plot of global population over the last 2,000 years. It looks like a simple exponential growth (something we examine in more depth in Chapter 2) but it is not. Exponential growth is bad enough—it is easy to be caught out by the way it surges upward. But this is far worse. Exponential growth has a constant doubling time—if it's exponential, a population doubles in size at fixed, equal time intervals. The doubling times for global population are marked on the figure. For the first 1,500 years, it is constant at about 750 years, but after that, starting with the Industrial Revolution, the doubling time halves, then halves again, then again. This behavior has been called "explosive growth"; it is harder to predict and results in a more sudden change. Malthus and the Club of Rome may have had the details wrong, but it seems they had the principle right.

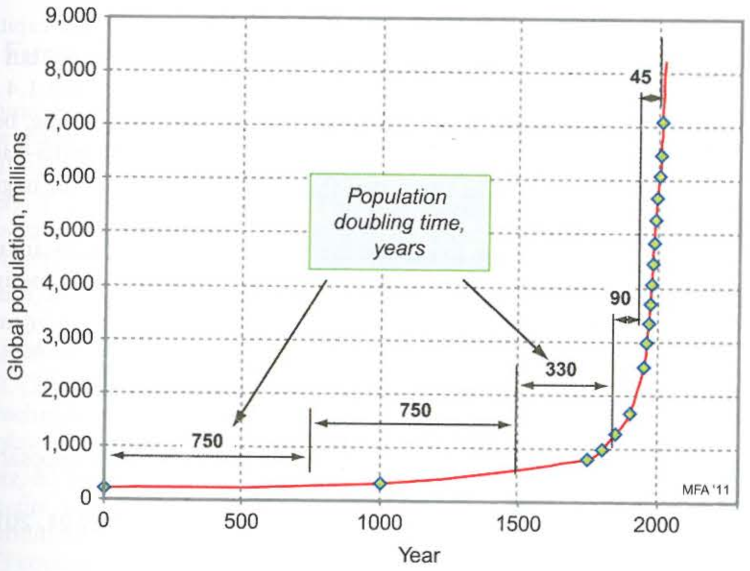

FIGURE 1.3 *Global population growth over the last 2,000 years, with the doubling times marked.*

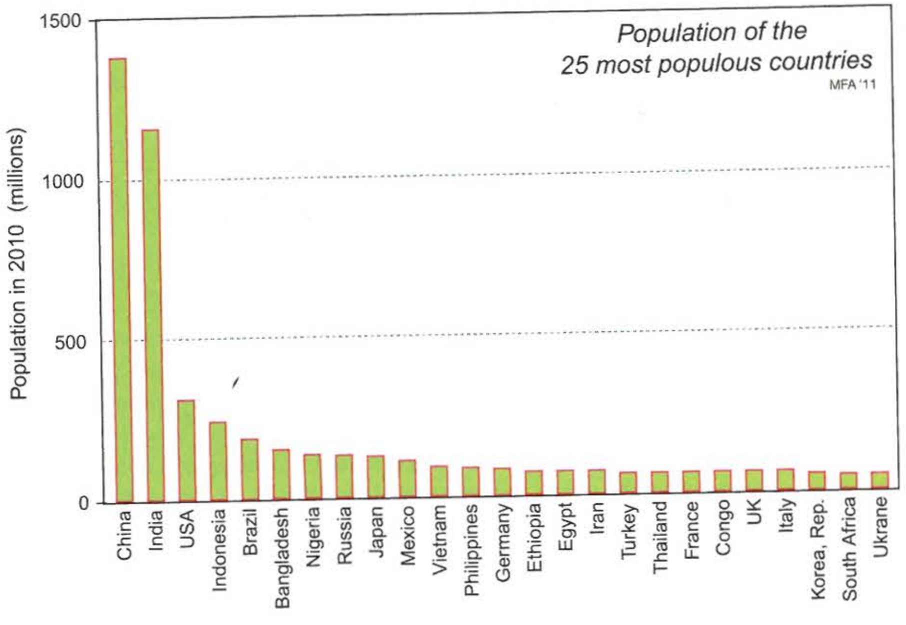

FIGURE 1.4 *The populations of the 25 most populous developed and developing countries in 2010.*

Global resource depletion scales with the population and with per-capita consumption. Per-capita consumption in developed countries is stabilizing, but in the emerging economies, as already said, it is growing more quickly. Figure 1.4 shows the distribution of population in the 25 most populous nations containing, between them, three quarters of the global total. The first two—China and India—account for 37% of the total, and it is in these two that material consumption is growing most rapidly.

Given all this, it make sense to explore the ways in which materials are used in design and how this might change as environmental prerogatives become increasingly pressing. The chapters that follow explore this.

News-clip: population, affluence, and consumption

Be a bull as China shops.

The world's largest population is enjoying rising wages and a growing disposable income. In short: 1.3 billion are rapidly becoming active consumers. . . .

***The Times*, May 21, 2011**

No further comment needed.

1.5 Summary and conclusions

Homo sapiens—that means us—differs from all other species in its competence in making things out of materials. We are not alone in the ability to *make*: termites build towers, birds build nests, beavers build dams; all creatures, in some way, make things. The difference lies in the *competence* demonstrated by man and in his extraordinary (there can be no other word) ability to expand and adapt that competence by research and development.

The timeline of Figure 1.1 illustrates this expansion. There is a tendency to think that progress of this sort started with the Industrial Revolution, but knowledge about and development of materials has a longer and more continuous history than that. The misconception arises because of the bursts of development in the 18th, 19th, and 20th centuries, and because the technological developments during the great eras of the Egyptian, Chinese, Greek, and Roman empires are forgotten. These empires did not just shape stone, clay, and wood, and forge and cast copper, tin, and lead, but they also found and mined the ores and imported them over great distances.

Importing tin from a remote outpost of the Roman empire (Cornwall, England, to Rome, Italy, 3,300 km by sea) to satisfy the demands of the Roman State hints at an emerging material dependence. The dependence has grown over time with the deployment of ever more man-made materials until today it is almost total. In reading this text, then, do so with the perspective that materials, our humble servants throughout history, have become, in another sense, our masters.

1.6 Further reading

Delmonte, J. (1985), *Origins of materials and processes*, Technomic Publishing Company, PA, USA. ISBN 87762-420-8. *(A compendium of information about materials in engineering, documenting the history)*

Flannery, T. (2010), *Here on earth*, The Text Publishing Company, Victoria, Australia. ISBN 978-1-92165-666-8. *(The latest of a series of books by Flannery documenting man's impact on the environment)*

Hamilton, C. (2010), *Requiem for a species: why we resist the truth about climate change*, Allen and Unwin, NSW, Australia. ISBN 978-1-74237-210-5. *(A profoundly pessimistic view of the future for humankind)*

Kent, R. (2009), "Plastics timeline," www.tangram.co.uk.TL-Polymer_Plastics_Timeline.html/. *(A web site devoted, like that of Material Designs, to the history of plastics)*

Lomberg, B., editor (2010), *Smart solutions to climate change: comparing costs and benefits*, Cambridge University Press, Cambridge, UK. ISBN 978-0-52113-856-7. *(A multiauthor text in the form of a debate ["The case for . . .," "The case against . . ."] covering climate engineering, carbon sequestration, methane mitigation, and market- and policy-driven adaptation)*

Lovelock, J. (2009), *The vanishing face of Gaia*, Penguin Books, Ltd., London, UK. ISBN 978-0-141-03925-1. *(James Lovelock reminds us that humans are just another species and that species have appeared and disappeared since the beginnings of life on earth.)*

Malthus, T.R. (1798), "An essay on the principle of population," London, Printed for Johnson, St. Paul's Church-yard. www.ac.wwu.edu/~stephan/malthus/malthus. *(The originator of the proposition that population growth must ultimately be limited by resource availability)*

Material Designs (2011), "A timeline of plastic," http://materialdesigns.wordpress.com/2009/08/06/a-timeline-of-plastics/. *(A web site devoted, like that of Kent, to the history of plastics)*

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W.W. (1972), *The limits to growth*, Universe Books, New York, NY, USA. *(The "Club of Rome" report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion)*

Meadows, D.H., Meadows, D.L., and Randers, J. (1992), *Beyond the limits*, Earthscan, London, UK. ISSN 0896-0615. *(The authors of The limits to growth use updated data and information to restate the case that continued population growth and consumption might outstrip the earth's natural capacities.)*

Nielsen, R. (2005), *The little green handbook*, Scribe Publications Pty Ltd., Carlton North, Victoria, Australia. ISBN 1-920769-30-7. *(A cold-blooded presentation and analysis of hard facts about population, land and water resources, energy, and social trends)*

Plimer, I. (2009), *Heaven and Earth—Global warming: the missing science*, Connor Publishing, Ballam, Victoria, Australia. ISBN 978-1-92142-114-3. *(Ian Plimer, Professor of Geology at the University of Adelaide, examines the history of climate change over a geological timescale, pointing out that everything that is happening now has happened many times in the past. A geo-historical perspective, very thoroughly documented.)*

Ricardo, D. (1817), "On the principles of political economy and taxation," John Murray, London, UK. www.econlib.org/library/Ricardo/ricP.html. *(Ricardo, like Malthus, foresaw the problems caused by exponential growth.)*

Schmidt-Bleek, F. (1997), *How much environment does the human being need—factor 10—the measure for an ecological economy*, Deutscher Taschenbuchverlag, Munich, Germany. ISBN 3-936279-00-4. *(Both Schmidt-Bleek and von Weizsäcker, referenced below, argue that sustainable development will require a drastic reduction in material consumption.)*

Singer, C., Holmyard, E.J., Hall, A.R., Williams, T.I., and Hollister-Short, G., editors (1954–2001), *A history of technology* (21 volumes), Oxford University Press, Oxford, UK. ISSN 0307-5451. *(A compilation of essays on aspects of technology, including materials)*

Tylecoate, R.F. (1992), *A history of metallurgy*, 2nd edition, The Institute of Materials, London, UK. ISBN 0-904357-066. *(A total-immersion course in the history of the extraction and use of metals from 6000 BC to 1976, told by an author with forensic talent and a love of detail)*

USGS (2002), Circular 2112, "Materials in the economy—material flows, scarcity and the environment," by L.W. Wagner, US Department of the Interior. www.usgs.gov. *(A readable and perceptive summary of the operation of the material supply chain, the risks to which it is exposed, and the environmental consequences of material production)*

von Weizsäcker, E., Lovins, A.B., and Lovins, L.H. (1997), *Factor four: doubling wealth, halving resource use*, Earthscan, London, UK. ISBN 1-85383-406-8; ISBN-13: 978-1-85383406-6. *(Both von Weizsäcker and Schmidt-Bleek, referenced above, argue that sustainable development will require a drastic reduction in material consumption.)*

1.7 Exercises

E1.1. Use Google to research the history and uses of one of the following materials:

- Tin
- Glass
- Cement
- Bakelite
- Titanium
- Carbon fiber
- Cobalt
- Neodymium

Present the result as a short report of about 100–200 words (roughly half a page). Imagine that you are preparing it for school children. Who used the material first? Why? What is exciting or remarkable about it? What do we use it for now? Do we now depend on it or could we live comfortably without it?

E1.2. There is international agreement that it is desirable (essential, in the view of some) to reduce global energy consumption. Producing materials from ores and feedstock requires energy (its "embodied energy"). The table lists the energy per kg and the annual consumption of four materials of engineering. If consumption of each could be reduced by 10%, which material offers the greatest global energy saving? Which the least?

Material	Embodied energy MJ/kg	Annual global consumption (metric ton/yr)
Steel	26	2.3×10^9
Aluminium alloys	200	3.7×10^7
Polyethylene	80	4.5×10^7
Concrete	1.2	1.5×10^{10}
Device-grade silicon	3,000	5×10^3