R&D challenges for the 21st century[†][‡]

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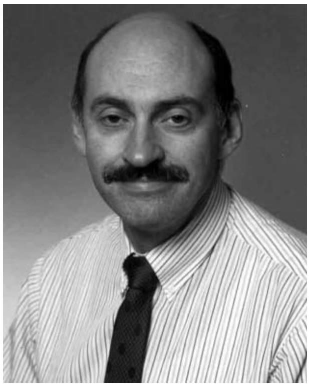
21st century industrial activities are faced with the challenge of sustainable development. The current state of affairs of the chemical industry as seen in its historical context offers a perspective for the future. The chemical industry developed in the 19th century from efforts to replace naturally occurring materials *e.g.* rubber and ivory. Revisiting nature for inspiration with today's far more advanced chemistry knowledge offers an abundance of opportunities for fundamental research as well as applied technology development with commercial perspectives. Beyond the covalent bond as practiced by synthetic petrochemistry for making a wealth of small-, oligo-, and macro-molecules there exists a vast area, barely explored, of bio-materials with seemingly endless structure-forming capability and functionality. These non-covalent, intermolecular forces working at several length and time scales define functional materials that may offer opportunities to tackle the challenges of sustainability. Such *bio-inspired materials* coming from a combination of synthetic polymer chemistry and chemistry inspired by nature form a future path to innovation and sustainable growth. They bring a basis for materials differentiation and renewed competitiveness in the chemical industry.

Introduction

Sustainability, innovation and high-throughput research are just a few of the buzzwords that bias the direction of R&D in the chemical industry at the beginning of the 21st century. In a broader sense however they express the underlying desire for industrial companies to be more environmentally friendly, to rejuvenate their growth potential and to do this faster than competitors. However, for many a contender the major challenge is the definition of the "what", *i.e.* what needs to be done in the short and long term to make this happen so that companies and their stakeholders can continue to prosper in a global, complex and very dynamic environment. There exists no "yellow brick road" to prosperity and many very smart people are searching to find solutions to the same challenges. Fortunately, there should be, as for any non-linear, complex system, multiple solutions that can meet the challenges of today's society.

The current state of affairs in the chemical industry as seen in its historical context offers a perspective for the future. Chemistry is still the key when looking at options for sustainable materials. Nature offers an abundance of examples and opportunities to shape structural and functional materials as demonstrated by the versatility offered through proteins, saccharides, and nucleotides. However substantial fundamental research as well as applied technology development is required to bring a commercially viable perspective to sustainable materials. For the last 60 years petrochemistry has dominated in making a wealth of small-, oligo-, and macro-molecules which form the basis of many materials. A cheap feedstock position has however slowed investigations into the structure forming richness of chiral molecules. The non-covalent, intermolecular force working at several length and time scales is one of nature's most effective tools that when well understood offers opportunities to tackle the challenges of sustainability with innovation for affordable growth



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and materials differentiation for competitiveness. The logic of encouraging research efforts in this direction can be understood when considering the state of the world and the important role the chemical industry plays in making a sustainable society possible.

State of the world

Like in many centuries before, the state of the world tends to be viewed with some level of pessimism for the future and an eye for imminent catastrophic events. In the 18th century Thomas Malthus published his hypothesis that (unchecked) population growth always exceeds the growth of means of subsistence.[1] Similarly in the second half of the 20th century The Club of Rome published several reports[2–4] on the dwindling of the earth's resources. They predicted the time of their end and offered scenarios of the impact hereof on global society. More recently and for that matter more talked about in view of (but unrelated) rising petroleum product prices, the end of the petroleum age is predicted. Based on the successful approach of M. King Hubbert,[5] a geophysicist correctly predicting the depletion of USA petroleum wells in the 1950's, the global crude oil production is estimated to peak between 2004 and 2008.[6,7] Such messages present society with important challenges. However, they mainly threaten the so-called developed Western world's quality of life and put a serious question as to the attainability for the developing and underdeveloped nations of similar standards of life. The World Resource Institute[8] quantified some of the worlds' realities (Table 1) concerning people, food, water, and environmental quality measures and put this into perspective as to the state of the individuals (Table 2). It suggests that the petroleum age which started about 60 years ago has fuelled an exponential population growth. Also it appears that only a minor percentage of people have benefited as to the quality of life increase as defined by the "First world". Although petroleum is an important energy source the majority of the developing world, and an estimated 2 billion people, still relies significantly on wood fuels (fuel wood, charcoal and wood-derived fuels), and crop- and animal waste as their prime and sole source of energy.[9] The same report and others[10] indicate—almost in a Malthusian way—that environments are changing through deforestation and urbanization. It suggests an ever increasing impact or footprint (defined as the land area required to provide the resources, *i.e.* grain, feed, wood, fish, and urban land, and absorb the emissions, *i.e.* carbon dioxide)[11] on nature and its resources that are available to sustain a global population[9,10]. The reports indicate that the challenges are global and that urgent measures need to be taken on a global basis. Some of the major challenges relate to:

Sustainability of the environment

Global climate change issues

Clean drinking water availability

Alternative energy sources

Products designed for reuse

New economic measures reflecting socially desirable goals.

Table 1 State of the world: 1950–2050[8 a]

	1950	1972	1997	2050
Population	2.5[b]	3.8[b]	5.8[b]	10.7[b]
Mega-cities[c]	2[d]	9[d]	25[d]	200[d]
Food[e]	1980	2450	2770	2200
Fisheries[f]	19	58	91	35
Water use[g]	1300	2600	4200	7500
Rainforest[h]	100	85	70	45
CO_2 emission[i]	1.6	4.9	7.0	14.0
Ozone layer[j]	—	1.4	3.0	7.0

[a] Source: World Resource Institute [b] Billions. [c] Population >8 million. [d] Millions. [e] Average daily food production in calories per capita. [f] Annual fish catch in millions of tons. [g] Annual use in cubic kilometres. [h] Index of forest cover; 1950 = 100. [i] Annual emissions in billions of tons of carbon. [j] Atmospheric concentration of CFC's in ppb.

Table 2 If the world were 100 people…[8]

- There would be 60 Asians, 13 Europeans, 13 Africans and 14 people from the western hemisphere.
- Half of the world's income would be produced by 12 people.
- 44 would not have access to proper sanitation.
- 22 would live on less than 1$ per day.
- 32 would be under the age of 15.
- 23 of those over the age of 15 would be unable to read or write.
- 2 would have a college education.
- 50 would not have made a phone call.

The laudability of setting these targets is clearly unquestionable but they neither suggest potential solutions nor the willingness of responsible bodies, if solutions are available or feasible, to act and implement them.

The chemical industry

In 2004, the world chemical industry is estimated to have generated €1.8 trillion in sales and to have employed 10 million people directly and another 50 million indirectly. About 33% of these sales were generated by the European Union (25 member states).[12] Although the chemical industry (Fig. 1) is very large, reaching all segments of the global economy from pharmaceuticals to base chemicals, it is fragmented and subject to profitability cycles.[13] A key reason for this is that the chemical industry is highly capital intensive, *i.e.* it requires substantial investments in manufacturing facilities (*e.g.* >€1 billion for a state of the art naphtha cracker to produce ethylene, >€100 million for a 250 000 mT polyethylene plant). Such investments that come on stream in large increments and with a substantial lead time affect the profitability cycle. As the maximum supply is fixed by the level of

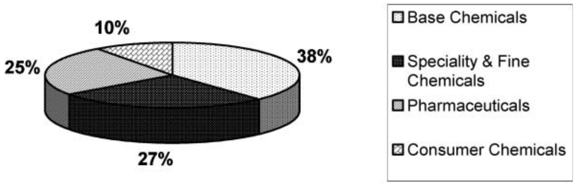


Fig. 1 The chemical industry is reaching all segments of the global economy from pharmaceuticals to base chemicals. The relative percentages for 2004 are represented.[12]

in-place capacity, prices will only rise if the demand catches up with in-place capacity, which is reflected over a 6–8 years period between the maximum profitability of assets. This is typical for so-called "commodities" that are driven by supply and demand. Commodities are products that may easily be substituted by another commodity producers' product indicating that pricing dominates the consumers' choices.[13] In contrast so-called "specialties" are less cyclical and more profitable as demand is driven by satisfying a customer need in markets that are willing to pay higher prices. Typically these markets are much smaller but margins are bigger and capital investments maybe somewhat smaller. As shareholders are often reluctant to view company profitability over the full cycle, companies are striving to move away from the cyclicality by various means such as differentiation and branding of commodities, establishing a dominating market share, and diversification into markets with out-of-phase cycles or less cyclical products.

At the beginning of the 21st century the chemical industry is considered a mature industry characterized by mergers and acquisitions, divestitures, consolidation, rationalization and cost management.[14] Rejuvenation and boosting momentum for a continued and sustainable growth requires new product development, new business building, innovative marketing and sales and different approaches to inventing products that meet the societal needs.[15] These efforts will need to comply with a multitude of socio-economic demands that are most simply expressed as the triple bottom line:

- Economic prosperity
- Environmental stewardship
- Societal responsibility

Beyond restructuring into commodity or specialty focused companies, or hybrids thereof, several programs have been put in place that reflect the commitment of the chemical industry to tackle the global challenges. These are foremost seen as commercial opportunities but the chemical industry evermore wants to be a responsible and equitable partner for academia and legislators. Responsible Care©[16] is one example of a code of conduct that sets the chemical industry on the road to sustainable development. In addition to codes of conduct turning the chemical industry into an agile one with acceptable profitability, a strong R&D effort oriented towards innovation is required.

R&D and innovation

The R&D function is traditionally the company's prime organization for discovering, inventing and developing the science and technology that anticipates product change, renews product offerings, and delivers the required technical knowledge that enables ultimate business success and overall company profitability. Industrial R&D activities have two complementing objectives: *value preservation*—to defend, support and grow existing businesses—and *value creation*—to advance and leverage technology platforms, and create new technologies that offer options for differentiation, financial growth and market expansion. The success or failure of these activities is typically associated with the clarity of the R&D goal *i.e.* the "what". The "what" definition is typically based on the current societal demands and the shortcomings of existing products. However, the translation of the "what" into an actionable program is complex and non-trivial and requires a very good understanding of the existing science and technology underpinning the current state of affairs. Creativity is then required to spot the options and define possible avenues towards an innovation or a solution to the set problem. These are often based on speculations or conjectures that need to be verified, tested and understood. The main activity of the R&D organization is the validation of conjectures or speculations, *i.e.* investigating the validity of a research hypothesis. A successful validation can lead to new product development. During the validation process, serendipity may lead to a discovery. Historical evidence indicates that R&D is an extremely risky undertaking as there is *a priori* no prescription for success. Although the statistics may vary depending on the industrial sector it is well known that the rate of transforming original ideas into commercial successes is very low—about 10% or less—but critically important to the long term survival of companies.[17] A recent study on the R&D investments of the world's top 1000 companies indicates that too much spending on R&D does not bring any extras in sales growth, profitability or shareholder return. Too little spending however will disadvantage the company unless a compelling rationale exists. The key to success seems to be an exceptional level of cross-functional cooperation among R&D, marketing, sales, and manufacturing which relates to the way a company generates, selects, develops, and commercializes ideas.[18]

A sustainable chemical industry

Sustainable development, typically defined as *meeting the needs of the present without compromising the ability of future generations to meet their own needs*,[19] is a vital objective for the chemical industry that focuses around feedstock and value added materials. The science and technology challenges that need to be overcome are significant and further compounded by societal and legal issues. The main industrial challenges revolve around four themes:

Energy cost associated with the production of the chemical industry's products and based on natural gas or petroleum derivates such as naphtha, which need to be acceptably priced as they define the competitiveness and sustainability of the economic position of companies.

Alternative feedstock, aligning to a drive to become less dependent on petroleum but still allowing the use of existing infrastructure in terms of logistics and manufacturing bases.

Reinvestment capital needs to be generated to enable production of same or renewable building blocks yielding preferably better products.

Materials of the future are similarly linked to the available chemical building blocks and their associated pricing to make them economically feasible.

Within these four themes R&D projects are viewed as long term and strategic. The risks are defined by the complexity of the science and technology challenge, the economic feasibility of the project results and their societal acceptance. For each theme active programs are in place but more significant efforts are required as reflected in the detailed roadmap for the chemical industry as proposed by CEFIC—the European Chemical Industry Council—*via* SUSCHEM—the European technology platform for sustainable chemistry.[20] The aim of this roadmap is to address the industry's challenges *via* a clear program that allows for public–private partnerships, an academic interest and the use of the latest science and technology, *e.g.* biotechnology. It reemphasizes the need for fundamental research and engineering science as this has been the key to the success of the chemical industry over the last 60 years.

Two areas of focus are distinguished: green chemistry and white/industrial biotechnology. Green chemistry refers to the use of renewable resources, *i.e.* biomass, to either obtain the same petrochemicals that feed existing manufacturing units or to provide alternative building blocks for making *e.g.* specialty chemicals, pharmaceuticals, colorants, surfactants, vitamins and food-additives. Traditional chemistry is used but nature's building blocks function as feedstock, *i.e.* saccharides, proteins, vegetable oils and lignin.

White/industrial biotechnology emphasizes the use of micro-organisms to provide either basic or specialty chemicals. It also includes the use of enzymes to catalyze and produce very specific products of extreme purity and compositional detail, *e.g.* peptides. The advancements in the field of genomics and proteomics drive these developments but important engineering challenges concerning yield, separation and purification remain to be resolved.

Sustainable materials

In the 19th and the first half of the 20th century, replacing dwindling supplies of naturally available materials, *e.g.* ivory and rubber, gave rise to the first beginnings of the chemical industry with a focus on synthetic materials, *i.e.* plastics. In the 20th century after WWII the chemical industry with an abundant supply of cheap petroleum experienced an exponential growth. The engineering feats for scale-up, supply chain integration and global reach facilitated by the information age gave the chemical industry its present mature status. Today, a key material produced by the chemical industry is plastic. The use of plastics encompasses all aspects of life reflecting its success and desirability. Unfortunately the growth perspectives of plastics are limited to that of the overall Gross Domestic Product growth, being typically 2–5% for the developed world. Given the 21st century drive for sustainability it appears that a certain analogy to the 19th century natural materials scare exists (at the time the supply of *e.g.* ivory and shellac became insufficient to meet the demand initiating efforts to find replacement materials). In view of an apparently dwindling petroleum feedstock it seems necessary to replace or surpass the performance of plastics/synthetic polymers using non-petroleum based building blocks and in addition creating new and sustainable growth opportunities. Just as plastics have replaced materials such as glass, metal and wood, and have created their own new markets, (*e.g.* electronics) as well as associated industries (*e.g.* additives and extrusion processing), it can be expected that new materials will create new industries over time. The difference with the 19th century efforts is that science and technology have advanced significantly providing insights and analytical tools allowing a better understanding of nature's materials. It is therefore even more surprising that until recently little attention has been given to the physico-chemistry and the materials science of nature's materials. Understanding and mimicking nature's structure-formation ability providing *bio-inspired* materials should therefore be a formidable area of research with significant opportunities for materials innovation.

In the future, plastics, just as wood, metals and glass, are materials that will not cease to exist. Bio-inspired materials are envisioned as the next generation of materials (Fig. 2). They can be defined as materials with structure-forming capacities that exploit molecular chirality and non-covalent bonds. Each is an essential driving mechanism for the very specific molecular association and self-organization of nature's building blocks, *i.e.* saccharides, amino acids, lipids and nucleotides. It goes far beyond the chemistry of step and chain growth polymerization as practiced for most common plastics today. Weak non-covalent bonds—hydrogen bonds, ionic bonds, and electrostatic and van der Waals interactions in combination with stereochemical features provide a broad field of mechanisms for oligomeric or polymeric molecules to associate in higher order structures creating unprecedented opportunities for innovative materials. Molecular self-assembly as a method of spontaneous organization is defined by the boundary conditions and introduces an additional versatility to structure formation. Different shapes and associated functionalities can be created with the same molecular structure by merely changing for example temperature and pH.[21,22]

Bio-inspired materials also surpass so-called bio-(degradable) polymers, *e.g.*

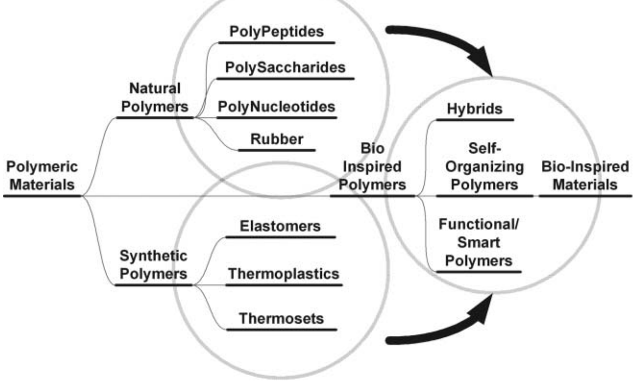


Fig. 2 The 19th century pioneers of synthetic polymers such as Charles Goodyear, Alexander Parkes and John Wessley-Hyatt aimed at the use and replacement of natural materials. The combined understanding of natural and synthetic polymer chemistry will lead to the advent of bio-inspired polymers in the 21st century exploiting the self-organization action of non-covalent molecular interactions explored by researchers such as Jean Marie Lehn and Bert Meijer.

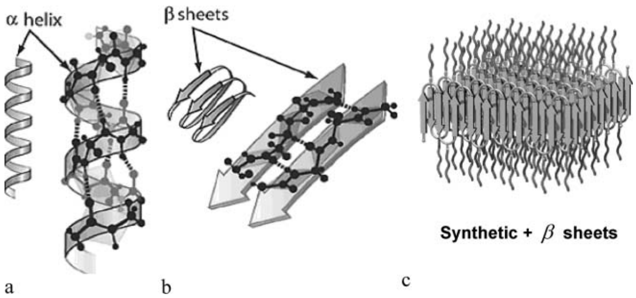


Fig. 3 Peptides may form secondary structures like a) alpha-helices or b) beta-sheets depending on their specific amino acid sequence and the boundary conditions. Each structure provides additional functionality in terms of its shape, beyond the chemical composition. In combination with synthetic monomers and oligomers the additional structure c) can be developed yielding hybrid polymers with very specific functionalities such as silk-like elasticity (image courtesy of J. van Hest).

polyhydroxyalkanoates, polylactic acid and polycaprolactone, which are synthetic polymers that have the additional property of being "compostable". Under specific conditions of temperature and humidity they decompose with time through the action of micro-organisms into essentially carbon dioxide and water. Although their utility is important to relatively small niche markets and their future market share may well expand, their market penetration remains limited to date. Key elements limiting their use are cost, performance and processing limitations, recycling issues, and structural consistency in view of biodegradability curtailing the range of applications.

Today, bio-inspired materials are in their infancy and significant R&D efforts are required to advance them to a commercial status. However their potential is undeniable in terms of the use of building blocks from renewable resources *e.g.* biomass, and the versatility of their chemistry. The use of building blocks from a vegetable or animal source is not new. Presently their relative use for materials synthesis compared to petrochemicals is small. However, vegetable oils from canola, sunflower or soybean provide an interesting feedstock—triglyceride fatty acids—that beyond their use in food allows additional chemistry that yields either opportunities for replacing petrochemicals or may be directly used to synthesize bio-inspired materials. Similarly, polysaccharides often referred to as cellulosics—starch or cellulose, chemically modified or not—being in use since the 19th century, offer interesting and versatile chemistry options. The full potential of such natural materials either as feedstock for components or as polymers by themselves can best be illustrated with proteins or peptides. Proteins are very long sequences of amino acids (>100) that can self-organize into alpha-helices or beta-sheets or just remain a random coil depending on the amino acid sequence and the boundary conditions. The chirality, *i.e.* the handedness of the amino acid, defines the alpha-helix to be either L or D, bringing an additional structural feature that determines the functionality or reactivity of the protein (Fig. 3). This principle also applies to short sequences of amino acids—3 and up—*i.e.* hydrogen bonds link the various molecules forming beta-sheets resulting in tape-like macromolecules (Fig. 4).[23,24] The wealth of substituent groups differentiating the amino acids can make such tape-like molecules for example hydrophobic on one side and hydrophilic on the other side. Depending on *e.g.* the type of solvent, pH, and peptide concentration (*i.e.* boundary conditions), further levels of organization become possible. Tapes can aggregate into ribbons, fibrils and fibers which eventually may form three dimensional porous structures that are either self supporting or gel-like. The chemical nature of the peptide can give rise to various higher order structures (Fig. 5).[23,24] Although this is fascinating physico-chemistry, at present the use of peptides is prohibitively expensive for any structural application when compared to current plastics. Still, the same physico-chemical principles can be used for less expensive systems. Block copolymers for example combining synthetic molecules with peptides can provide an important route to novel materials that show unique properties. The self-assembly is driven by the peptide indicating that the structure-forming capacity of the molecules is reversible in view of the temporal nature of the hydrogen bond. Accordingly a novel way to form macromolecules is established with the added features of reversibility and functionality. The same principle can be driven even further to traditional petrochemical building blocks. It was demonstrated with the 2-ureido-4[1*H*]-pyrimidinones.[25,26] These small molecules associate through four directed hydrogen bonds yielding an elastomeric plastic, which upon heating or dissolution will reversibly turn into a low molecular mass liquid.

Conclusions

The chemical industry, even when considered as mature, continues to search for new but sustainable growth

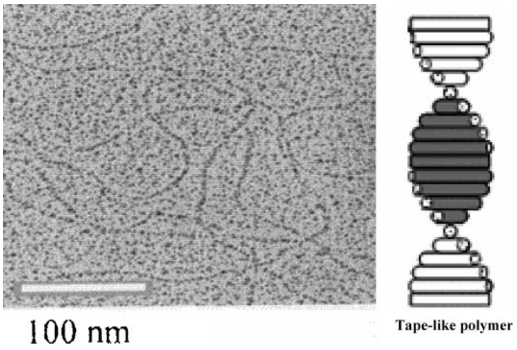
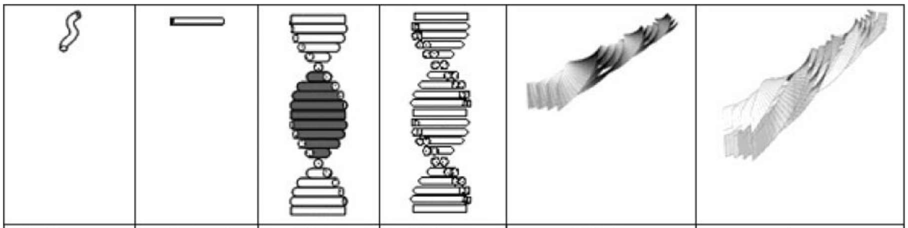


Fig. 4 Peptides of a few amino acids will self-assemble into beta-sheets to form tape-like macromolecules due to H-bonding between the individual peptides.[23,24] The amino acid substituent groups will extend from the beta-sheet plane above and below, and define the functionality of the tape like macromolecule (not shown)(image courtesy of A. Aggeli).



Peptide	Rod-like monomer	Tape	Ribbon	Fibril	Fiber
Width		1-10 nm	2-10 nm		
Length		Up to 100 nm	Up to μm	Up to 100 μm	Up to 100 μm
Persistence length		~10 nm	~100 nm	~μm	~μm
		Semi-Flexible	Semi-Flexible	Semi-Rigid	Semi-Rigid

Fig. 5 Peptides of a few amino-acids (3–25) will self-assemble into various shapes depending on the boundary conditions (concentration, solvent, pH). The rod-like monomer may form tape-like beta sheets that in turn may associate to form ribbons, fibrils and fibers[23,24](image courtesy of A. Aggeli, S. Scanlon).

opportunities through science and technology. The chemical industry's versatility, touching every aspect of life with its products, makes it an essential partner in the development of innovative options that ensure a sustainable quality of life. In the short term, viable alternative feedstock solutions that allow for the continued use of existing infra-structure will be essential for success. In a later stage alternative feedstock for different chemistries and potential new performance options requiring different business models and infra-structure will determine the agility and competitiveness of the companies. All this will continually be governed by the principles of affordability, a willingness to follow up on the vision with action and money, and the ever changing global economic realities.

The success of green chemistry and white/industrial biotechnology will also be defined by the ability to develop advanced engineering solutions including process intensification and efficiency keeping the cost position at a par with the best in the class.

Bio-inspired materials offer a future direction for developing a novel class of materials that is both sustainable and technologically different offering tailored functionality and versatility as inspired by nature. There are many examples in the scientific literature where nature inspired physico-chemists to shape structures.[27] Many of these research efforts are still at an early stage but are advancing rapidly towards real materials opportunities. Plenty of knowledge needs to be gained to fully understand all the consequences of the mechanisms of non-covalent bond associations at the various length scales. Early adopters of these principles most probably will be found in the pharmaceutical or medical field as the bio-inspired material and associated products are commercialized on performance and not on price. Bio-inspired materials can be anticipated to complement and partially replace the existing materials base similar to plastics complementing metals and ceramics. Driving the science and technology forward will require a multidisciplinary approach bringing chemists, physicists, mathematicians, biologists, engineers and much other expertise together in a focused effort. The cases presented here are just a sampler to indicate that chemistry still has a lot to offer in terms of materials innovation.

References

1 T. Malthus, *An essay on the principle of population, as it affects the future improvement of society with remarks on the speculations of Mr. Godwin, M. Condorcet, and other writers*, J. Johnson, St-Paul's Church Yard, London, 1798.
2 D. H. Meadows, *The limits to growth*, Universe Book, New York, 1972.
3 D. Meadows, J. Randers and D. Meadows, *Limits to growth*, Chelsea Green Publishing, Post Mills, VT, 2004.
4 D. Meadows, D. Meadows and J. Randers, *Beyond the limits*, Chelsea Green Publishing Company, Post Mills, VT, 1992.
5 K. M. Hubbert, Energy from fossil fuels, *Science*, 1949, **109**, 103.
6 P. Raeburn, The end of oil, *Scientific American*, 2001, **October**.
7 C. Campbell and J. Laherrere, The end of cheap oil, *Scientific American*, 1998, **March**.
8 *EarthTrends: The environmental Information Portal*, WRI, 2005, http://earthtrends.wri.org/datatables/index.php?theme=4.
9 *Renewables in global energy supply. An IEA factsheet*, IEA, 2005, http://www.iea.org/dbtw-wpd/Textbase/Papers/2006/renewable_factsheet.pdf.
10 *Living planet report*, WWF, 2002, http://www.panda.org/news_facts/publications/key_publications/living_planet_report/lpr02/index.cfm.
11 M. Wackernagel, Tracking the ecological overshoot of the human economy, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 14, 9266–9271.
12 *Facts and figures. The European chemical industry in a worldwide perspective*, CEFIC, Brussels, 2005, pp. 90—91, http://www.cefic.org/factsandfigures/.
13 *The global chemical industry in the 21st century*, SRI, 1999, pp. 79—83, http://www.sri.com.
14 L. Dranikoff, T. Koller and A. Schneider, Divestiture: Strategy's missing link, *Harvard Business Review*, 2002, **May**, pp. 74–83.
15 T. A. Stewart, *The wealth of knowledge*, Nicholas Brealey, London, 2001.
16 *Annual report 2004/2005. Responsible Care. Making strides in Europe and the world*, CEFIC, Brussels, 2005, http://www.responsiblecare.org.
17 A. C. G. de Kok, *Master of Business Administration Thesis*, Critical Success Factors in New Product Development, 2003, University of Liverpool, Liverpool.
18 B. Jaruzelski, K. Dehoff and R. Bordia, *The Booz Allen Hamilton global innovation 1000*, Booz Allen Hamilton, VA, USA, 2005.
19 World Commission on Environment and Development, *Our common future*, Oxford: Oxford University Press, 1987.
20 *Sustainable chemistry strategic research agenda 2005 – Innovation for a better*

future. 2005, SUSCHEM, http://www.SusChem.org.
21 D. A. W. Thompson, *On growth and form*, Dover, New York, 1992.
22 S. Hyde, *The language of shape*, 1997, Elsevier, Amsterdam.
23 A. Aggeli, Responsive gels formed by the spontaneous self-assembly of peptides into polymeric beta-sheet tapes, *Nature*, 1997, **386**, 259–262.
24 A. Aggeli, Hierarchical self-assembly of chiral rod-like molecules as model for peptide beta-sheet tapes, ribbons, fibrils, and fibers, *Proc. Natl. Acad. Sci. U. S. A.*, 2001, **98**, 21, 11857–11862.
25 R. M. Versteegen, *PhD Thesis*, 2003, Technical University Eindhoven, Eindhoven.
26 S. H. M. Sontjens, *PhD Thesis*, 2002,Technical University Eindhoven, Eindhoven.
27 S. Mann, *Biomemetic materials chemistry*, Wiley-VCH, New York, 1996.