MATERIALS

Materials for Design

Chris Lefteri

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Dedication: For my mum and dad, Androulla and Stasi.
I owe it all to you.

LAURENCE KING

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INTRODUCTION

This book is for anyone interested in or involved in designing with physical materials. It is not a scientific or historical analysis of materials, but instead serves as an aid to understanding the current state of materials – which are the most commonly used and which are potentially the materials of the future. It embraces all areas of design and production, from products made as one offs to those mass-produced in the scale of millions of units per year, from highly desirable design pieces to some of the everyday objects that we take for granted. I first started writing about materials in 1999 and I stated then that we were only at the beginning of our exploration into this area: fourteen years later this still remains true, and a significant development is that material innovations are not just coming from the science community but increasingly from designers themselves. This book is a celebration of the range of established materials that designers are innovating with and materials that they are creating from scratch.

'Like trying to capture a family photograph when all the family members are moving', is how Ezio Manzini described materials in 1989 in his book *The Material of Invention*. As time accelerates the introduction of new types of materials, so the classification of materials families continually needs to be redefined. The established descriptions that have been used to define materials families such as plastics, metals and woods seem to become less and less relevant. With the blurring of the boundaries between these materials families, it's getting harder to work with the old definitions. For example, plastics are more and more often encroaching on the territories of other materials, such as innovations in bioplastics made from cellulose fibres or plastics that are taking the place of metals for lightweight, corrosion-resistant applications.

Alongside the evolution of new technologies and grades of materials, something else is happening that is changing the value they have in our lives. This is not linked to the science of new materials but concerns the role they play in contemporary life. Materials are increasingly becoming central characters in consumer focused stories: anti-bacterial surfaces to improve hygiene; advanced composites that define luxury in consumer electronics; authentic 'real' materials in interiors like stone, glass and stainless steel; the use of 'eco' materials to alleviate our guilt and make us feel like more caring consumers.

These material stories not only help brands differentiate themselves from each other, but facilitate designs that drive a desire in consumers to buy into these stories. However, beyond this desire, there is also a genuine initiative to find alternative, sustainable sources of materials. This area is being driven as much by science as it is by ever-curious designers like Suzanne Lee, with her marvellous innovation of a material grown from bacterial cellulose (see page 60), who are increasingly developing the actual materials themselves rather than merely just applying materials in designs as an afterthought.

So, as innovations in materials continues to take place unabated, why is this a good moment to take a breath and consider the role of materials and how they might be applied in design? Partly because looking at design through the lens of materials is always an interesting place to see updates and new innovations, but also because the world and the connection we have with materials is going through an incredible change, driven by the two main themes of desire for materials stories and a need to find sustainable solutions. As a result, the use of materials is becoming much more important for designers, not just through developing new materials but also by having a better understanding of their properties and values. This book takes a snapshot of over one hundred raw materials and presents key information that that designers should know about when considering materials for design.

Unlike the materials revolution of the last hundred years, the next materials age won't be as visible. It won't lead to the kind of visions of the future that we had in the 1950s, with a Jetson's-style future of pastel-coloured, aerodynamic vehicles flying about our heads. The themes will be many, but for sure they will be driven by low-energy production and applications, materials scarcity and new interactions with materials. Some materials innovations are, unlike plastics, metals or ceramics, invisible: for example, the information that you receive on your phone, laptop, TV, or the increasing number of other screen-based electronic devices will change the physical interaction you have with materials rather than change the way they look; our need to explore new sources of energy might mean that the road you drive down won't just be a path for cars, but a surface to generate electricity; the walls of a room won't simply be a place to decorate with your favourite colour but where you choose the functions that best suit your home – noise reduction, smell neutralisation, pollution killing. This book would be doubled in size if it were to include all of these types of materials technologies, and perhaps they will form a second instalment.

The three sections in this book are not based on the traditional definitions of materials but instead are categorized through the provenance of these materials. As our focus on the need to reduce resources continues, then where materials originate – whether grown, mined or oil based – becomes more important. The selection of materials within each of these sections is not exhaustive but instead attempts to capture those materials that are the most useable, used, important or just downright inspiring for designers. For some materials the case-studies that accompany them are from specific designers, such as the lightweight aluminium 2012 Olympic torch by Barber Osgerby (see page 174), and in some cases they are from everyday products that are typified by their use of the particular material, such as the crafting of willow for cricket bats (see page 42). The selection is based on raw materials – steel, oak, polystyrene, soda-lime glass for example – and not semi-formed materials that have been transformed into sheets (such as well known brands like Corian® or Lycra®). The information given for all the materials is kept consistent, allowing for cross-referencing across the properties of different types of materials. Where costs have been included, it should be noted that prices fluctuate and those given are estimates that should be used for comparative purposes only.

I hope that this book will make you ever more curious about the materials of today, tomorrow and the not-so-distant future. Please dig in and enjoy!

Chris Lefteri
London, 2013

GROWN

Welcome to the wondrous world of grown materials: fish leather, textiles created from bacteria and horsehair, plastic made from chicken feathers, and the more usual grown materials such as plant fibres and wood. This section is one of the major emerging materials families, an area that encompasses both the big chemical industries – who are looking into extracting proteins from starch to make new types of plastic – as well as research projects from individuals like Fiorenzo Omenetto, a scientist who is developing an incredible array of uses for silk.

This section includes experimental projects based on byproducts of natural waste which are deconstructed to make new types of materials. The urgent need to find rapidly renewable materials is driving designers to experiment with waste materials, for example Erik De Laurens is making a new composite from fish scales, and the rapidly renewable and biodegradable mycelium (grown from the roots of mushrooms in a matter of days) is being used to replace expanded polystyrene.

If, as the introduction to this book points out, one of the key drivers for materials development is the need to find more sustainable materials, then most of these innovations can be found in this section. The last century will be remembered as a time when classical notions of production were blown apart by plastics derived from oil. The next century might see a time when our plastics and products don't come from machines but are grown. Graze across the crunchy textures, playful interactions, natural patterns and interesting surfaces of materials that are currently being developed.

Red Cedar *(Juniperus spp.)*

As a schoolboy lacking in concentration, I found something incredibly therapeutic about sharpening a pencil. Whether it's with an old fashioned magnesium sharpener or a razor-edged steel craft knife, there is no mistaking the peppery smell of that sharpened pencil and, for some, the irresistible urge to gnaw on the end of one. As an object made of wood it is one that has a direct immediacy with its user. You hold it, digging your nail into its plastic-painted surface, smell it, carve it into a needle sharp point, and chew it. Through its built-in obsolescence it goes from being an object of satisfying proportions to a redundant little stump. For this once young schoolboy it also evokes memories of a material and product that empowered me to express my early designs for intergalactic space ships.

One of the reasons that the pencil provokes such strong associations is due to its aromatic smell, which comes from the use of red cedar, a timber with a reddish-brown heartwood and a smooth, fine grain. Since the first mass-produced pencils were developed in Germany in the seventeenth century they have continued to evolve into a product of high mass production. One of the curious facts about pencils is that 75 per cent of pencils sold in the US are yellow, which apparently is due to an old standard established in the nineteenth century, where yellow was used as a symbol of prestige.

Image: Cedar pencil

Production
Pencil cedar can be worked easily with both hand and machine tools with little blunting effect on blades. It will tend to split if nailed and has poor steam-bending properties.

Sustainability issues
According to the IUCN (International Union for Conservation of Nature) red cedar is one of the least threatened trees.

+	–
–Easy to work	–Prone to splitting
–Aromatic scent	–Poor steam bending
–Straight, even grain	
–Sustainable	

Key features

- Medium density: 380 kg/m^3 (23 lbs/ft^3)
- Straight, fine, even grain
- Aromatic scent
- Low stiffness
- Not suited to steam bending

Cost

The most common type of cedar is the western red variety. It is moderately priced and can easily be found on the market.

Sources

Mainly Eastern USA and Canada, Uganda, Kenya and Tanzania.

Typical applications

The aroma of cedar has been put to use for products such as cigar boxes, wardrobes and chests – to ward away moths – coffins and furniture veneers. Waste shavings from production are often distilled for use in essential oils.

Pine *(Pinus sylvestris)*

The name pine suggests scented temperate forest, but it's impossible to describe pine as a specific wood, because it's actually a family of woods, which includes trees with evocative names such as sugar pine and Table Mountain pine, as well as the perhaps more well known Scots pine, spruce pine and yellow pine. Its timber ranges from a gummy, resinous wood to a warm toasted blonde pine, with a white sapwood and a heartwood varying from light yellow-brown to reddish brown, often with a faint scent of resin.

Pines are one of the most widely recognized and used timbers, chosen mainly for their good range of structural properties, including strength, stiffness, good workability, excellent stability and low shrinkage. Due to the fact that its growth range varies from hot to cold climates, the weight of pines greatly varies. Although pine is itself a family it is also part of a larger group that, together with spruce and larch, is known under the collective name of 'deal', a term used to describe coniferous softwoods.

Apart from scented forests, the other association of pine is its 'country kitchen' aesthetic, which seemed to dominate European kitchen design for a large part of the late twentieth century. In contrast, what I like about the Favela armchair by Fernando and Humberto Campana is the adhoc nature of the design and construction, something that seems appropriate for a timber with so many diverse applications.

Image: Favela chair, Fernando + Humberto Campana

+	–
–Easy to work –Good dimensional stability –Accepts finishes well –Sustainable	–Not especially strong –Dead knots can drop out of the wood

Production
Pines are generally easy to work; however, the sticky resin in some pines can be problematic. Dead knots can also give problems by dropping out. They glue well unless the piece of wood is particularly resinous. They also accept stains, paints, oil and lacquers well.

Sustainability issues
Pines are a fast growing tree and so can be seen as renewable under the correct forestry stewardship. One of the interesting aspects of pine trees in relation to their growth is that they are often planted next to 'nurse' oak trees, which protect the pine saplings from wind while allowing sunlight to penetrate.

Cost
Most pines are generally moderately priced.

Sources
Mainly Canada and the USA, UK, mainland Europe and the Scandinavian countries; however, pine grows in countries as far south as Portugal and as far north as Siberia. The colder the climate, the slower the growth and the better the quality.

Key features
• 390-690 kg/m^3 (24-43 lbs/ft^3)
Straight even grain
• Easy to work
• Finishes well
• Low shrinkage
• Low strength

Typical applications
The excellent stability of pine makes it particularly suitable for pattern making, doors and drawing boards. It is also used for light and medium construction, boat building, joinery and furniture making and telegraph poles. Like Maple, pines are also valued for their by-products. The resin secreted by pines has a large number of uses that include resin, tar and turpentine.

Douglas Fir *(Pseudotsuga menziesii)*

Plastic will always be plastic. Of course, each type of this vast family is different but if one creates a grade of polypropylene then, without fail, it will always be the same, no matter how many different products you make from it. However, the biography for many grown materials is a chronicle of sustained weather and geography. Unlike wine, a product so distinctly affected by nature, where the history of the grape is reflected in its taste, the history of wood affects the way it functions and looks, with the grain storing the memories of time and of place.

For me, there is nothing like the distinctive, unpretentious markings of Douglas fir. Douglas fir is perhaps not as recognized and well known as other softwood timbers, such as pine or cedar, but it does have wonderful colouring and grain. In terms of colouring, it has a warm honey colour with rich, wide reddish-brown bands of heartwood, which are contrasted by early and late wood. This colouring, combined with wonderful, wavy tiger-like markings, and its rich, sweet and spicy scent set it apart from other softwoods. Also known as British Columbian pine, Columbian pine, Douglas fir, red and yellow fir and Oregon pine it stands alone as its own species and is not a pine.

Image: Crate Wardrobe by Jasper Morrison

Production
Available in long lengths and clear grades, which are generally knot-free, it is easy to work but does have a blunting effect on saws, which need to be kept sharp. Care should also be taken with fast-grown timber as it may split when cut across the grain. A good finish can be achieved with Douglas fir, but the distinctive grain can have a tendency to rise after polishing and therefore will require more finishing. It also glues well.

Sustainability issues
Douglas fir does not appear on any of three main appendixes of the CITES list of endangered species. It is a fast-growing tree, and can therefore be viewed as renewable under the correct forestry stewardship.

+	–
–Fairly knot-free –Easy to work –High stiffness and bending strength –Renewable	–Prone to splitting if cut across the grain –Requires more finishing than other timbers

Cost
Compared with other timbers, Douglas fir is moderately priced.

Sources
Although grown throughout the world, most Douglas fir comes from the USA and Canada. Other areas include the UK, France, Australia and New Zealand.

Key features

- 530 kg/m^3 (33 lbs/ft^3)
- High stiffness
- High crushing strength
- High bending strength
- High resin content
- Fairly knot-free

Typical applications
Suitable for exterior joinery with sapwood excluded (preservative treatment not required, but could be beneficial), interior joinery, fittings and furniture, which is generally unpainted to make the most of the figure and flooring. In heavy industry it is also used for construction work and railway sleepers. Douglas fir is also one of the world's biggest sources for plywood.

Poplar *(Populus spp.)*

Wood is not generally perceived as a material of mass production. Of course, it is used in all manner of high-volume products but not in the same way as moulded plastic or metal are, where identical parts come off a production line in their millions. Wood just isn't seen as a material from which billions of identical products are produced. Ikea has wooden furniture, but the furniture is still assembled by hand. Here, however, is a wooden product that is as mass produced as a glass lightbulb and as abundant as a plastic ballpoint pen.

The matchstick, along with the toothpick, is high up in terms of stratospheric production volumes. The matchstick uses poplar's ability to burn easily without producing toxins, and a lot of finely tuned production is involved in making just a single match. During the process there is no human contact with the products. First, the wood is cut into sheets of veneer, which are then chopped into square splints. The splints are then fed into a series of holes within metal plates, at a rate of approximately 40,000 matches every minute. These plates carry the matches through the various stages of production and the evidence of them can be seen at the base of every match – have a look for the rounded edge at the base of a match. The matches are dipped into a chemical bath to prevent afterglow when the match is burned, and then they are taken through paraffin to help them burn more easily. Machines can yield approximately 55 million units per day.

Image: Abundantly produced matchsticks

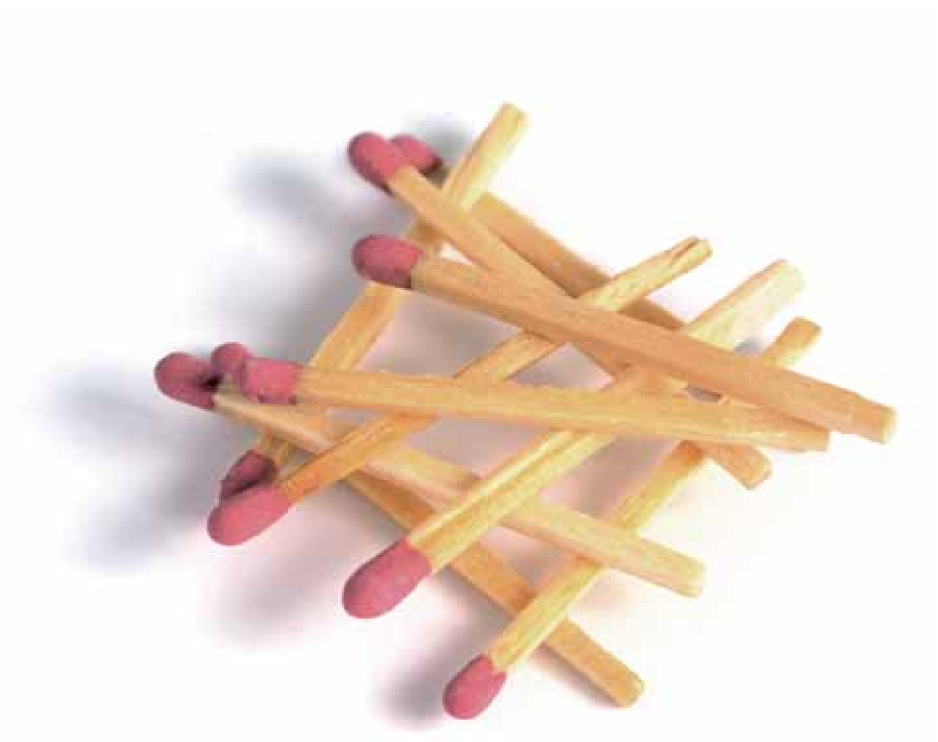
+	–
–Tough	–Poor steam bending
–Good resistance to splintering	–Perishable
–Easy to work	–Low shock resistance
–Sustainable	–Poor finishing

Production
Its straight grain makes poplar a wood that has good workability. however, it does have poor steam-bending properties. Staining poplar can produce patchy results.

Sustainability issues
Poplars are a fast growing tree, and therefore can be viewed as renewable under the correct forestry stewardship. They can also be grown in relatively poor soils and fully grown poplar are effective carbon sinks.

Key features
- 448 kg/m^3 (28 lbs/ft^3)
- Pale colouring
- Tough for its weight
- Straight but woolly grained
- Good resistance to splintering
- Low resistance to shock
- Low stiffness
- Liable to insect attack

Sources
Europe, USA and Canada.



Typical applications
Don't let the use of poplar for matchsticks allow you to underestimate it. It has been used in far more tough applications, for example as break blocks for railway wagons, boxes and crates and also interior joinery and turned products such as toys. It is also a common veneer in the construction of plywood.

Cost
Poplar is relatively inexpensive.

Yew *(Taxus baccata)*

If you are writing a book about materials, it should include products that exhibit functions which best exploit the material. As an example of a wood with good tensile strength, there can't be many better examples than an archer's bow, a wonderful demonstration of opposing mechanical properties in a single piece of wood.

The key to designing a bow is in understanding the contrast of tension that is needed on the outside of the bow – known as the backside – and the forces of compression required on the inside – called the belly. The traditional choice of wood for the elegant and flexible, traditional longbow is European yew.

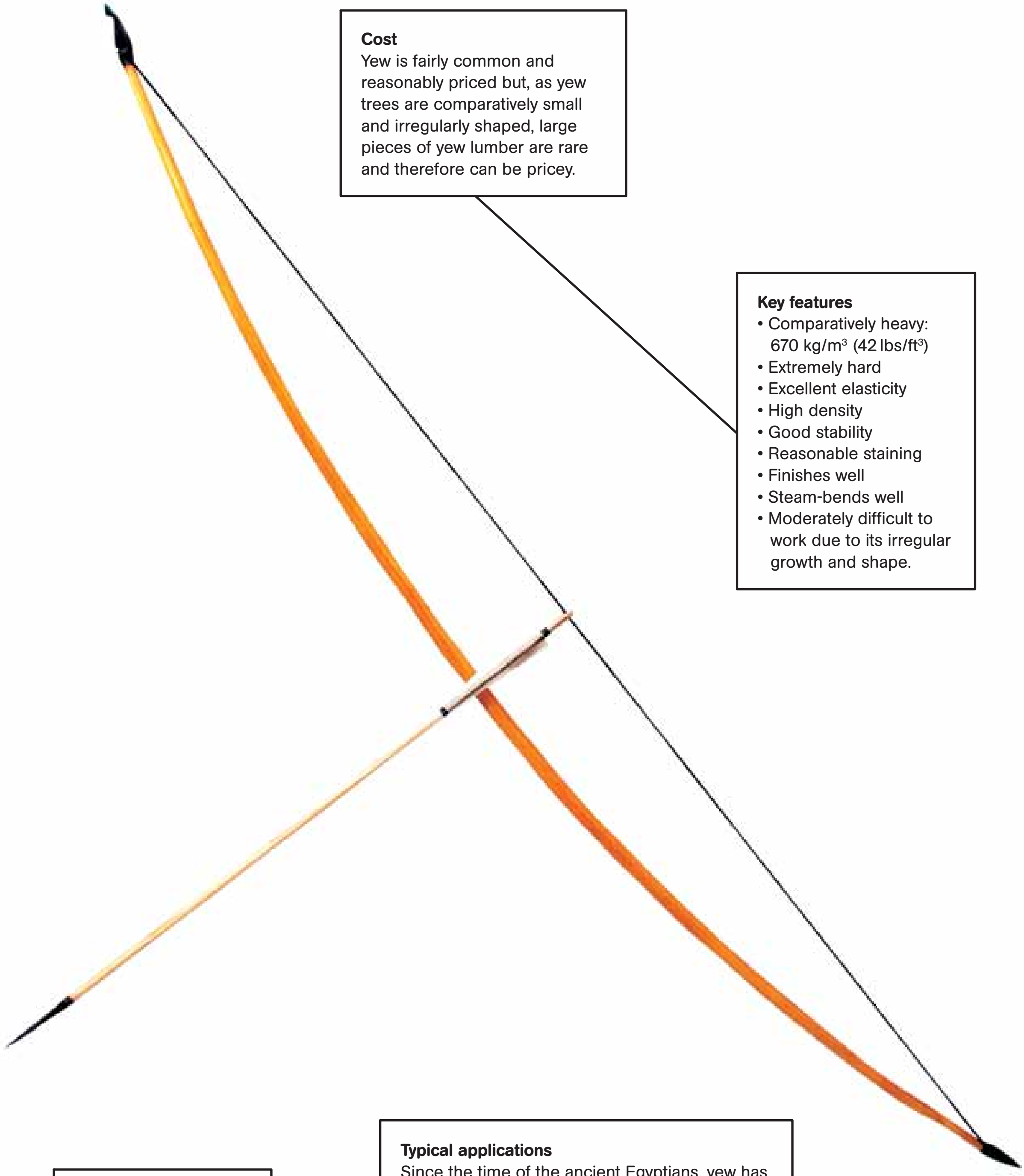
A natural lamination process provides the contrast of the heartwood – the inner core of the tree – which displays good resistance to compression, and the sapwood – the wood near the outer part of the trunk – which has good elasticity in tension, which means that a single piece of yew fulfils both of these physical criteria. When other woods are used in bows, designs sometimes feature a composite of wood varieties. In some instances, hickory is used on the backside and hornbeam for the belly side. In Asia, a combination of horn on the belly side and animal sinew on the backside gives the bow an explosive shot. As with many natural materials, wood has more recently been replaced by sophisticated composites of carbon and fibreglass in contemporary archery competitions.

Image: Yew longbow

+	–
–Excellent strength and elasticity –Good stability –Very good steam bending –Highly decorative	–Difficult to work

Production
If balsa and lime are *the* soft hardwood, then yew is *the* hard softwood, making it a difficult wood to work. Yew also sits together with ash, birch, elm, hickory, oak and walnut as a good wood for steam bending. This is a process that can be done as an industrial production or in a home workshop.

Sustainability issues
There are fewer yew trees now than previously, as with many natural species utilized by mankind. Considering the great strength, durability and beauty of the timber it could be seen as a shame that many of the uses for which yew was perfect are now met by iron. The species is further threatened by felling, partly due to rising demand from pharmaceutical companies that extract an anti-cancer property, Taxol, from the leaves of cultivated species.



Cost
Yew is fairly common and reasonably priced but, as yew trees are comparatively small and irregularly shaped, large pieces of yew lumber are rare and therefore can be pricey.

Key features

- Comparatively heavy: 670 kg/m^3 (42 lbs/ft^3)
- Extremely hard
- Excellent elasticity
- High density
- Good stability
- Reasonable staining
- Finishes well
- Steam-bends well
- Moderately difficult to work due to its irregular growth and shape.

Sources
Throughout Europe, Scandinavia, Algeria, Asia Minor, northern Iran, the Himalayas and Burma.

Typical applications
Since the time of the ancient Egyptians, yew has been a symbol of everlasting life and this is why you are likely to find so many yew trees planted in churchyards and cemeteries. As such, it has often been referred to in literature, ranging from the yew bows referred to in Tolkien to the yew wands in the Harry Potter series. Beyond this, it is very good for turning and furniture, and it also makes an exceptionally decorative veneer. It is the wood traditionally used for Windsor chairs.

European Lime *(Tilia x europaea)*

Ask enough adults what their favourite material memory is from childhood and the chances are that a high proportion will say wood. Not necessarily a wooden toy but just a chunk of wood, because with a soft piece of wood you can whittle it down to make virtually anything, from airplanes to dolls. Of course children are not going to be familiar with the exact type of wood, but if they were to choose a wood that was soft and easy to cut then they could choose no better than a piece of lime.

Creamy yellow rather than porcelain pale like Japanese maple, lime is the carver's wood and – like balsa and boxwood – it is one of those contradictory timbers that is a soft hardwood. With its pale close grain and resistance to splitting lime, or basswood as it is sometimes known, is used as the main timber for whittling to create intricate and complex shapes that would be difficult to achieve with many other woods. As such it adds to the craft palette because like no other material, wood, and lime in particular, can empower budding designers and craftsmen. It has such immediate accessibility, requiring only a simple saw, a hammer and nails, some sandpaper and glue to turn even the simplest blocks into toy animals. Lime is a timber that for thousands of years has provided craftsmen with the perfect material for carving.

Image: Toy by Ooh Look it's a Rabbit

Production
Lime's close grain is one of the keys to its resistance to splitting and the reason it carves so well. However, this softness can result in a woolly surface texture. It does not steam bend particularly well but does finish well with stains and varnishes.

Sustainability issues
This wood species is not listed in the CITES appendices of endangered species.

+	–
–Easy to work, being particularly good for carving –Glues and finishes well –Straight, even grain –Sustainable	–Its softness can result in a fuzzy surface –Poor steam bending

Key features
- Lightweight: 535 kg/m^3 (34 lbs/ft^3)
- Soft and easy to carve
- Excellent resistance to splitting
- Easy to work
- Low stiffness
- Odour free
- Straight, uniform and fine grain

Cost
Lime is relatively inexpensive.

Sources
Throughout Europe and the UK. In the USA it is referred to as American lime or Basswood.

Typical applications
Due to its ability to resist splitting, lime finds its best use as a wood for carving. This feature is also utilized for cutting boards in leatherwork and pattern making. It has a wide range of uses for turned products, hat blocks and artificial limbs, and its lack of a strong smell also results in its use in food containers. One of the interesting by-products of lime is 'wood wool', which is used as a packing material and is the result of thin shavings.

Oak *(Quercus)*

The coarse, open-grained and tan-coloured timber from the revered oak tree has more than 200 different species but perhaps even more rich, cultural associations. Its particular Englishness is captured in this quote by British furniture writer Aidan Walker:

'There is no tree more closely associated with the history and patriotic fervour of a nation, no tree considered to have served a nation so well and so consistently as the oak for Britain'.

Unlike any other material family, only a wood can generate this level of affection. Like so many materials, its qualities have echoes in the English language – from the Latin name *Quercus robur*, we take the word robust – and as such oak is metaphorically and practically and strong material.

It comes as no surprise that oak even enters our sensorial palette, going beyond its appearance to evoke tastes and aromas: it is used to make wine and whiskey casks, with the tannic acid in the wood fibres imparting a distinctive flavour. This application is also a testament to the air- and liquid tight properties of oak. It is also used for smoking cheese and ham. Beyond these qualities, oak is characterized by its crushing strength, toughness, density and, like yew, ash, birch, elm, walnut and hickory, is very good for steam bending.

Image: Campo Arata tables, Paolo Pallucco

+	–
–Extremely versatile –Easy to work –Strong and hard –Takes finishes well –Good water resistance –Distinctive patterns	–Coarse texture –Some sustainability issues

Production
As with all timbers, and indeed natural materials, the harvesting and the cutting of the material can yield different end results in terms of performance and aesthetic. The quarter cutting of oak, for example, gives a distinctive pattern of broad rays. It can be easily sliced for veneers, can be readily carved and is excellent for steam bending. When cutting, oak can blunt tools quickly but it takes various finishes such as waxing, dying and polishing very well.

Typical applications
Beyond its use for smoking ham or in wine and whiskey barrels, it is used for wood-ash glazes for ceramics and the tanning of leather. It is one of the most widely used hardwoods for general purposes. Good quality oak is used for a range of furniture, flooring, boat building, liquor barrels, frames in buildings, doors, panelling, church pews and ecclesiastical sculptures, and carving.

Cost
Oak is around the middle of the price spectrum for hardwoods.

Sources
Temperate climates of the northern hemisphere of Europe, Asia Minor, North Africa and Eastern USA.

Sustainability issues
Oakwoods have diminished greatly in the UK over the last few hundred years, but the Forestry Commission is now actively promoting woodland planting with native tree species. A fungal disease known as 'sudden oak death' exists in Europe, and although the disease affects many other species including rhododendron, viburnum, beech, sweet chestnut and holm oak, at present native oaks appear to be relatively resistant to it. However, it may pose a threat to oaks in the future – particularly if the trees become stressed by climate change. Another, more worrying effect known as 'acute oak decline' has recently been identified in the UK which kills native oaks and its causes have yet to be understood.

Key features
- 720 kg/m^3 (41 lbs/ft^3)
- Course texture
- Straight grained
- Good workability
- Good finishing
- Rich grain
- Good water resistance

European Beech *(Fagus sylvatica)*

By beech I mean European beech, a plain, creamy brown wood sprinkled with an even distribution of fine flecks, as opposed to American beech, which has bolder pattern and more reddish colouring. Whichever beech you look at, it's never been considered a flashy timber – it doesn't overflow with the rich surfaces of tropical timbers or the tiger-like markings of Douglas fir. Although the actual tree is majestic, beech timber is a practical wood that has very good uniform density, a quality that allows it to be easily shaped and which has resulted in it being the workhorse of wooden products and utility furniture.

Beech is a valuable wood and is one of the most widely used in the UK. It is used for many things, from the utility furniture found in school classrooms across the country to domestic kitchens. In terms of its qualities, it is strong, finishes well, can be easily worked and, as a result, is used for a variety of applications. Beech will always remind me of school furniture and, in particular, a desk that found a new home as my mother-in-law's kitchen table, a table distinctly different from traditional kitchen tables in its colouring and grain, because it is made from beech.

In fact, it is the simple grain and even colouring of beech that has also resulted in it being a wood that is often stained to imitate more exotic woods such as mahogany and walnut. Perhaps one the reasons that Thonet used beech for his bentwood chairs at the beginning of the nineteenth century.

Image: Patricia Urquiola side tables for Artelano

+	–
–Easy to work –Excellent strength –Versatile –Steam bends well –Sustainable	–Can warp or split if incorrectly dried –Not the most attractive wood, with simple grain and uniform colour

Production
Beech, as exemplified in the iconic Thonet bentwood cafe chairs, is an excellent wood for steam bending, together with ash, birch, elm, hickory, oak, walnut and yew. This is a process which can be done in industrial production or in a home workshop. Aside from steam bending, beech also planes to a good finish but can have a tendency to burn if tools are not kept sharp. It can also be turned and carved easily. It tends to split if nailed.

Sustainability issues
European beech does not appear on any of three main appendixes of the CITES list of endangered species.

Cost
Beech is an economically priced wood.

Typical applications
Because of its cost effectiveness and good general working properties, beech is one of the best general-purpose woods and is used in a massive variety of applications. These include the curved forms of shoe lasts and shoe trees or ergonomic tool handles, toys, furniture, brush handles, cabinet making, sports goods, toys, turnery, kitchen utensils, chopping boards, laboratories and parts for musical instruments.

Sources
Central Europe and West Asia.

Key features
- Medium density: 720 kg/m^3 (45 lbs/ft^3)
- Close, consistent straight grain
- Excellent strength
- Good workability
- Finishes very well
- Can warp or split if incorrectly dried
- Steam bends well

Rock Maple *(Acer saccharum)*

From the hardness of rock maple to the easier to work soft maple or the almost translucent, porcelain coloured grain of Japanese maple, and from the springiness of skateboards to the hardness of bowling alley floors, maples are characterized as being the timber of hardness and resilience. Apart from soft maple, which has a more distinctive wavy and warmer, reddish tinge, most maples are typified and easy to spot due to an even, creamy-white texture.

The use of the extremely hard, crisp, even texture of creamy-white maple allows for the surface of these knives to be extended beyond traditional wooden handles. The knives are dominated less by the steel and more by natural grain of the wood. The use of maple in these products exploits the high strength and abrasion resistance of this particular wood – the reason it is the material of choice for bowling alley lanes. Compared with other strong woods like oak it has more flexing strength but with similar crushing strength.

Apart from its flat even grain and hardness, one of the other traits of maple is when it is sliced through a part of the tree that exhibits irregular growth it creates what is known as the distinctive 'bird's-eye' maple pattern.

Image: Fusion maple knives by Andrea Ponti

+	–
–Extremely hard and resilient –High wear resistance –Steam bends well –Sustainable	–Can cause allergies –Susceptible to insect attack

Production
Good for steam bending but, unless working with soft maple, it is more difficult to work with tools, which it tends to blunt fairly quickly. It finishes with stains and polishes reasonably well. It needs to be pre-bored for nailing and screwing.

Typical applications
Its good strength and resistance to wear make it an excellent timber for domestic and industrial flooring, particularly squash courts, bowling alleys and roller-skating rinks. Also used for shoe lasts, rollers in textile production, furniture and turned ware.
Maple syrup is also a derivative of the maple tree. Birdseye maple is sometime referred to as 'fiddleback maple' due to its use for violin backs. Jaguar use two kinds of veneer F in its car interiors: walnut F bur for the top of the range models and birdseye maple F for its executive cars. The springy toughness of maple is also put to full use in skateboards, which take advantage of a high strength-to-weight ratio.

Key features
- $720\ kg/m^3$ ($45\ lbs/ft^3$)
- High resistance to abrasion and wear
- Reasonable staining and finishing
- Fine and even texture
- Usually straight grained
- Medium density
- Steam bends very well

Sources
Rock maple is grown largely in Canada and Eastern USA, although there are many other varieties of maples that grow throughout Europe and Asia Minor.

Sustainability issues
This wood is not listed in the CITES appendices of endangered species.

Cost
Moderately priced.

Teak *(Tectona grandis)*

Teak has a rare combination of physical and mechanical properties. Although it has a medium density and hardness, it is the natural oiliness – which is obvious when you touch teak – that distinguishes it from other timbers by furnishing it with a natural weatherability, thereby eliminating the need for preservatives and making it maintenance free. Apart from this oiliness it has other properties that make it a very sensorial timber. It has a rich, tigerish, syrupy brown grain and a distinctive smell, especially when it is freshly cut. Perhaps this is the reason it belongs to the aromatic *Lamiaceae* family, which includes herbs such as sage, oregano, basil and rosemary.

As one of the most solid and durable of timbers, there are many stories of its extreme hardness, some illustrating how this was enhanced by burying the timber under damp earth for several years. This method was used to harden the teak for construction of traditional Chines Junks. It is these properties that are similar to Iroko, which is often used as an alternative to teak. But, as anyone with teak garden furniture will know, without regular oiling this rich, warm-coloured wood weathers to a cool silvery grey.

There is also another more serious side to teak production, with regard to deforestation. As teak consumption grows, large parts of indigenous forest in Myanmar are suffering and, although Myanmar has the largest indigenous forests in Indonesia, through state owned plantations, is also responsible for managed teak forests.

Image: Teak bench by Wolfgang Pichler

+	–
–Good hardness –Steam bends well –Good chemical resistance	–Relatively brittle –Sustainability issues in India and Indonesia –Does not accept finishes well

Production
A wood of medium density and hardness, it can be steam bent to a moderate radius. The reason for its good weathering properties – the natural oils which clog the pores – means that it does not accept lacquers, varnishes or stains well. It is relatively brittle and not suited for applications like tool handles or sporting goods which require good impact strength or bending strength.

Sustainability issues
It takes around 100 years for teak to mature into timber and although the trees are common, the indigenous forests of India and Myanmar are under threat due to over-exploitation. As a result Myanmar has banned raw log exports but timber smuggling is common. However, according to the International Union for Conservation of Nature teak is classified as a timber of 'Least Concern'. There is also a market in South East Asia for recycling teak from old warehouses into furniture.

Typical applications
The highly resistant nature of teak makes it particularly suited to exterior applications, especially in abrasive areas such as those near salt water: here it is used for boat decking, general construction, docks, and bridges. It is also widely used for exterior garden and park furniture. Its advantage in these public areas is that, although its colouring weathers over time from rich golden-brown to silver-grey, it does not need – and indeed does not accept – preservatives. Beyond these general applications teak is used in acid-resistant applications such as chemical ducts and vats and laboratory benches. Other non-structural applications include medicinal uses in south East Asia.

Sources
Teak is indigenous to India and South East Asia, with Myanmar accounting for most of the world's teak. Managed forests in Indonesia are also a source of teak.

Key features
- Medium density: 630-720 kg/m^3 (38-43 lbs/ft^3)
- Good hardness
- Good steam bending
- Excellent dimensional stability in a wide range of temperatures
- Good resistance to chemicals
- Relatively brittle
- Moderately easy to work

Cost
Teak is around five times more expensive than oak, and is sometimes referred to as the 'platinum of woods'.

European Walnut *(Juglans regia)*

Wood is for many people a status symbol. Like the metals family, wood carries with it a rich history of associations, references and stories. Combined with the decadent smell of leather, the interior of a car is one of the places where these aspirational qualities are valued most highly. Even with cutting-edge technology elsewhere in the car and the use of advanced materials, wood still occupies a strong position in creating consumer stories.

Walnut is one of those woods that is as famous for its natural decorative qualities as it is for the fruit that it bears. From the period of around 1620–1720, which became the 'Age of Walnut' due its use in fine English furniture, to its use in that most British of cars, the Jaguar, there are strong associations surrounding this wood. There are three main groups, and European walnut is distinguished from American or South American walnut by having a more wavy pattern and being a warmer brown, but all have similar working properties. Its mechanical properties are characterized by medium bending strength comparable to beech, high crushing strength and stiffness.

Apart from the trunk, the roots of walnut also provide a good source of timber which is why it is sometimes dug around. Besides its fruit the walnut tree has other by-products such as tannin, which can be distilled from the leaves to make an antidote to poison. The nuts are also well known for their oil.

Image: Quasi table by Aranda/Lasc

+	–
–Easy to work –Steam bends very well –Highly decorative finish	–Becoming unsustainable, so limited availability –Relatively high cost

Production
As with all timbers, and indeed living things, the harvesting and the cutting of the material can yield different end results in terms of performance and aesthetic. One of the prominent uses of walnut is the slicing or the tree into veneers to sometimes produce what is known as a walnut burr, where the grain runs in all directions providing a look much admired in antique furniture and the interior of the Jaguar car, where it is coated with a durable polyester wax-free coating to enhance the toughness and assure that these symbols of success fulfil their long-term warranties. Walnut has very good steam-bending properties and it stains and finishes very well.

Sustainability issues
According to research by Purdue University in the USA, potentially warmer, drier summers and extreme weather events as the climate changes could possibly be fatal for walnut trees. In the UK Jaguar has sponsored a 72 hectare community woodland project planted with walnut trees.

Sources
European walnut grows in the UK, France, Italy, Spain, Asia Minor and South West Asia.

Cost
Relatively high cost.

Key features
- Medium density: 610 kg/m³ (40 lbs/ft³)
- Hard and resilient
- Colour can vary
- Natural wavy grain
- Steam bends well
- Easy to work
- Finishes well

Typical applications
Throughout European history walnut has been used for fine cabinet work and high-end applications for gun and rifle stocks, shop fittings, furniture and interior joinery. It is used as a highly desirable decorative veneer for furniture, interiors and car dash-boards. It has a moderate durability but there are far more suitable timbers for exterior applications.

European Birch *(Betula pendula)*

Birch trees are good peelers, which is why birch is one of the best-known timbers for plywood. Apart from the fact that it can be easily sliced, another reason for such widespread use in plywood is that birch is a hardwood that is dense, strong and straight with a fine, pale brown colour that means it can easily be stained and finished to fit varied applications. It is its visual blandness that allows it to be so adaptable and to be stained to look like other, heavier woods, such as maple or cherry, making it extremely versatile in designs where light-coloured wood is required.

Birch trees were among the first to recolonize the rocky, ice-scoured landscapes after the glaciers of the last ice age receded; therefore it is often referred to as a pioneer species. The silver birch – another name for European birch – is distributed throughout almost all of Europe and Asia Minor. The downy birch, one of the very few native trees of Iceland, also occurs throughout much of Europe and north Asia.

There are many species of birch, which vary slightly in look and properties. The wood of yellow birch and sweet birch is heavy, hard and strong, while that of paper birch is lighter, and less hard, strong and stiff. All birches have a fine, uniform texture. Paper birch is easy to work with hand tools; sweet birch and yellow birch are difficult to work with hand tools and difficult to glue, but easily machined.

Image: Four Birds Table by Simon Mount

Production
Apart from being good for slicing to make veneers and taking coloured stains very well, the other noteworthy characteristic of European birch is its ease of working by hand or with power tools.

Sustainability issues
Birch does not appear on any of three main appendixes of the CITES list of endangered species.

+	–
–Easy to work –Steam bends well –Strong and relatively light –Sustainable	–Not suited to outdoor use –Looks bland unless stained

Typical applications
Birch is the principal material for birch plywood and is also used for furniture, general turnery such as brush or broom handles, bobbins and dowels. Waste from birch is also often used in pulp for paper production, the sap can be used to make beer and the bark can be used to produce methyl salicylate, the main component of aspirin. Birch is also likely to be the wood from which disposable cutlery is made.

Sources
European birch, or silver birch, is grown throughout Europe and Scandinavia; however, the birch family (*Betula spp.*) is composed of 30 to 50 species growing in Asia, North America and Europe.

Key features
- 580 kg/m^3 (40 lbs/ft^3)
- Straight, fine textured and close grain
- Steam bends well
- Easy to work
- Stains and polishes to a good finish
- Good strength
- Low resistance for outdoor use

Cost
Compared to other timbers European birch is moderately priced and comparable to oak or maple in cost.

European Ash *(Fraxinus excelsior)*

There are many stories in folklore that feature trees, including tales where they are the key to immortality or, in the case of the ash tree, where they can induce a fear of snakes if one stands near to the rustling of its leaves. Beyond these ancient tales, ash has been used throughout history in a number of applications, from transport to weapons of war, and ash is well known as a tough and flexible hardwood. In fact, it is one of the toughest European timbers around.

It is these key characteristics of supreme flexibility and good shock absorption, in both its natural state and also when it is steamed, that sets ash apart from other timbers. This combination of qualities comes from the dense hardness of growth rings from the summer months combined with the lighter spring growth, which provides what can best be described as a natural lamination process.

Furniture designer Joseph Walsh has taken olive ash, which is the dark heartwood of ash trees rather than a specific species, and applied it to a series of pieces called 'Enignum'. Through these pieces, Joseph demonstrates the strength and flexibility of the wood by producing forms that gracefully curve, twist and bend into highly evocative shapes. He uses a highly experimental process to achieve the pieces, an approach that has led to the discovery of a new and undisclosed way of fabricating using the wood.

Image: Enignum lounge, Joseph Walsh

+	–
–Very tough and flexible –Easy to work –Steam bends well –Excellent shock absorbency –Sustainable	–Perishable and susceptible to insect attack –Low stiffness

Production
Ash machines well with little blunting of tools and can be planed to a very high smooth finish. Its flexibility, together with birch, beech, oak, walnut and yew, makes it ideal for steam bending.

Sustainability issues
Ash does not appear on any of three main appendixes of the CITES list of endangered species, however ash dieback has been observed in a large number of trees in eastern and northern Europe in recent years.

Key features

- High density: 680 kg/m^3 (40 lbs/ft^3)
- Colour ranges from pure, lustrous white through to pale and creamy
- Outstanding flexibility and toughness
- Straight grained
- Course texture
- Steam-bends well

Cost
Compared with other timbers, European ash is moderately priced and comparable to oak in cost.

Sources
Northern and Central Europe, North Africa and Western Asia.

Typical applications
Its excellent shock absorbency makes it a good timber for railway coach construction, hockey sticks, baseball bats, snooker cues, cricket stumps, gym equipment and tool handles for hammers and shovels, where good shock absorbency is vital. It is also used for making oars for boats, and has been used for other transport applications, such as early cars and aircraft. Its suitability for bending means that it is also used for walking stick handles and chairs. Like aspen, it is also used in food packaging due to its low odour and lack of tendency to impart a taste.

Aspen *(Populus tremuloides)*

Aspen is a clean, anaemically pale hardwood that grows mainly in northern parts of Europe, the USA and Canada. One of the main characteristics of aspen is its very low thermal conductivity, which is why it is ideal for benches and wall linings in saunas – it's the reason you don't burn when your bare skin makes contact with the wall in the sauna. This attribute is also connected to one of the reasons it is used for making matchsticks: it burns very slowly. But in the application of aspen discussed here, it is the functionality of a surface in relation to its sensory and functional properties that is important.

Textile Wood is a project that expresses the ever-increasing and diverse range of adjectives used in connection with materials – this one in particular conjures up a unique type of imagery. By giving your material invention an identity, such as Textile Wood, you are bound to create an evocative buzz in people's imaginations, and when they get their hands on an actual sample of the material they won't be disappointed. Inspired by a college project centred on creating quiet environments, Textile Wood's Finnish inventor, Tero Pelto-Uotila, treats solid aspen timber with a high-pressure water jet, which raises the grain to a level that, in Tero's words, is 'dense and hairy'. The soft, fibrous texture of Textile Wood also contributes to another key property: enhanced sound absorption.

Image: Textile wood by Woodloop

+	–
–Low thermal conductivity	–Poor steam bending
–Lightweight	–Tends to warp and twist
–Machines well	
–Suited to outdoor use	
–Sustainable	

Production
The texture is produced by a water jet which raises the grain. The material can be cut in the same way as standard aspen.

Typical applications
Aspen is the traditional material for making clogs, hat blocks, doors, brush backs, mouldings, textile rollers, toys, kitchen utensils, interior parts of furniture, baskets, chopsticks, matchsticks, fruit baskets and crates. Important specialized uses include sauna linings, because of its low conductivity of heat, and chopsticks. Its light weight means it is often used as part of the construction in sports equipment, for applications such as hockey sticks. Also, because of its lack of odour, it is often used in food packaging and containers.

Sustainability issues
Aspens are known for seeding and thriving in places where fires have been. It stands moisture well and ages very slowly without any chemical treatments needed – one of the reasons it is used in outdoor furniture. It is used to replace pressure-treated woods as an ecological alternative.

Key features
- Low density: 417 kg/m^3 (25 lbs/ft^3)
- Fine texture and pale colouring
- Straight, very subtle, even grain
- Easily machined
- Low thermal conductivity
- Low bending strength
- Natural stain residence
- Inclined to warp and twist

Cost
Aspen is a relatively inexpensive hardwood. Although, interestingly, it is softer than some soft woods such as pine.

Sources
Northern Europe, Canada and north-eastern and north-central USA.

Willow *(Salix spp.)*

Willow is to England like Teak is to Asia, both evoking particular associations: with willow it is cricket greens and the sound of leather against the creamy wood. Willow is a wonderfully adaptable tree, used for everything from flood defences to basket weaving. Its timber can easily be carved, and is most famously used for the crafting of cricket bats. The use of willow in basket making is a uniquely honest process, where the designer is not only processing the materials and converting them into objects, but also growing and harvesting them. The process of making wicker begins with the material in its most natural state. Lee Dalby, one of the UK's most well-known wicker craftsmen, describes cultivating willow in the winter, 'it is important to be involved in the seasonal process. This time of year the sap is in the ground and not in the fibres, which makes the wood too soft. The branches are bundled to let them dry out ready for working. When they are ready to be woven they can be soaked to make them malleable and soft to weave'.

The true definition of wicker is woven willow, and there are two main types of construction recognized in the ancient process of basket making: the frame basket, where the basket is built around a frame made from a variety of materials, and the stake and strand basket, where the starting point is a base that is made by working upwards to the top. The tree yields off-shoots and branches that grow in long, uninterrupted lengths, making willow an ideal material for weaving.

Image: Gunn and Moore English willow cricket bat

+	–
–Easy to work –Shock resistant –Lightweight –Flexible –Sustainable	–Poor steam bending

Production
In the form of wickerwork, willow is hand woven to make anything from architectural structures to baskets. Surprisingly, however, it is poor for steam bending.

Sustainability issues
Willow is rapid growing, and because it is often planted by river banks, where its roots reinforce the banks, it has a role to play in nature conservation and soil erosion. In the Netherlands it is also used to stabilize sea defences by the use of 'polder' mats – huge woven mats of willow which are sunk into the water.

Key features

- Comparatively lightweight: 450 kg/m^3 (28 lbs/ft^3)
- Straight, fine and even grained
- Easy to work
- Resilient to cracking
- Shock resistant
- Good flexibility

Sources

Willow grows mainly in Europe, Western Asia, North Africa and the USA. The cultivation of willow for cricket bats is undertaken largely by specialist UK growers.

Cost

Solid willow is moderately priced and willow reeds are inexpensive.

Typical applications

Apart from cricket bat blades and wickerwork, willow is also used for crates, toys, clogs and flooring, and it is sliced and used for decorative moiré veneers. Apart from these design-focused applications, the willow tree is also planted by riverbanks, where its roots reinforce the banks.

Boxwood *(Buxus sempervirens)*

Some of the materials in this book were selected because they fascinate me; some because they are part of the standard palette of materials for designers; some because they point towards new future scenarios; and some just because I fell in love with the marriage of material and product. In the case of boxwood, it was chosen because of its use within a product.

Combs are products that have been made with materials of symbolic reference throughout the ages. From precious metals, such as silver, through to aluminium – when aluminium was commercially introduced at the end of the nineteenth century – and on to exotic tortoiseshell and cellulose acetate plastic, which is a plastic alternative to the exotic shell. And then again, on to the simple boxwood combs that are a part of Japanese culture.

Beyond the symbolic use of these materials in such small-scale products, it's easy to identify good, practical choices of materials in the making of combs. A good use of materials in this application can range from the softness and warmth of the material in the hand to its flexibility, so that it doesn't break as it pulls knots out of the hair. As a result, it is a product that needs such fine detailing that when the material or the production is wrong it is easy to see. Boxwood, with its orange-tanned fine grain, is the perfect wood for a comb.

Image: Boxwood comb

+	–
–Ideal for carving and lathe work –Finishes well –Good flexibility	–Only suited to small-scale applications –Slow growing

Production
Boxwood never grows much beyond the height of a small tree or bush, therefore planks are generally small and so not the best material for the production of large furniture; instead, it is much more suited to small-scale applications, such as the comb.

Sustainability issues
Slow growing, however it is not listed on CITES list of endangered species.

Sources
Boxwood has a number of different origins, all of which affect its naming, including Iranian, Persian and Turkish.

Typical applications
The weight and density of the grain and the fact that it can easily be carved has resulted in boxwood being used for small products, such as rulers and measuring instruments, trinket boxes, chess pieces and musical instruments.

Cost
It's the delicate carving and historical beauty of boxwood combs that make them expensive. The material itself is cheaper than those used for the same purpose, like tortoiseshell or ivory, although within the wood family it is an expensive option due to its increasing scarcity and slow growth.

Key features
- Relatively heavy: 885 kg/m^3 (55 lbs/ft^3)
- Light, even grain
- Ideal for carving
- Can be turned well on a lathe
- Produces a fine finish
- Good flexibility

Balsa *(Ochroma pyramidale)*

Being a hardwood that can be cut with a craft knife has made balsa the ultimate wood of empowerment and placed it at the heart of millions of children's play factories. Balsa wood evokes many material memories, with its powdery white, lightweight warm surface which can be scored with a fingernail. It is recognized as the best material to work with simple tools, and has an informality and accessibility compared to some of the more noble woods such oak.

It is easy to forget that the physical properties and appearance of wood are dictated by the climatic conditions in those parts of the world in which it is grown. This richness of variation in growing environments gives it something like the qualities we associate with wine. Species like bamboo and balsa are the results of a rich and warm climate with plenty of rainfall and good drainage, which enables the trees to grow rapidly. It is this rapid growth that produces featherweight wood, which gives it the highest strength-to-weight ratio of any wood – although it is not technically the lightest wood in the world, as two or three other plants classified as wood, but not usable in the same way, are lighter.

Today, most commercial-grade balsa comes from Equador, which has the ideal geography and climate for growing the tree. The word balsa derives from the Spanish word for raft, reflecting its excellent buoyancy properties. In Ecuador, this quality is further reflected as the wood is known as Boya, which means buoy.

Image: Riley Classic balsa surfboard fin

+	–
–Very good strength-to-weight ratio –Extremely buoyant –Easy to work –Good shock absorbency –Sustainable	–Poor steam bending –Extremely porous so tends to soak up stain

Production
As every child who has ever played with balsa wood will know, it is very soft and can be cut with basic crafts tools. Its open structure also means that it absorbs stains very well, but it does soak up a lot of the stain.

Sustainability issues
The speed of growth accounts for the lightness of this wood. It can grow up to 30 m (100 ft) in 10-15 years and as it's so light it is easy to harvest and transport. Although wild balsa has gradually been disappearing, it has been successfully grown under plantation conditions.

Cost
Balsa is relatively inexpensive.

Typical applications
Apart from model aircraft, it is also used for speed boats, heat, sound and vibration insulation, buoyancy in lifebelts and water sports equipment, theatre props, surfboards, and even as the skeleton for planes in World War II.

Sources
Central and South America, particularly Equador.

Key features
- Very light: 40 kg/m^3 ($2\frac{1}{2}$ lbs/ft^3)
- Good shock and vibration absorption
- Can be easily glued and cut
- Poor steam bending
- Extremely easy to work

Hickory *(Carya spp)*

Materials that promise to enhance performance proliferate new products, and this 'performance enhancing' label is one that anyone buying any type of consumer product can recognize. As a materials family, woods are not generally considered as being able to contribute much to these material stories in the way that those such as progressive and advanced carbon fibre or high-tech ceramics like alumina do, but in relation to natural materials hickory is 'the' performance timber.

Hickory is not strong and dependable in the way that oak is characterized, but more 'high performance' in a way that can be likened to sports performance. As testament to these high-performance characteristics, hickory has many applications in sports, largely due to its ability to absorb physical shock without breaking, and it has the natural ability to enhance the functionality of the user.

Like so many modern performance materials that sit outside of the wood family it is the combination of properties, rather than any distinctive grain or colour, that make the pale-coloured hickory stand out. Its straight and even grain gives it properties of shock and energy absorption, an ability to not splinter when flexed, and a high stiffness that is valued in as the handles for tools such as hammers.

Image: Hickory drum sticks

+	–
–Extremely shock resistant –Strong and stiff –Does not splinter –Steam bends well –Sustainable	–Difficult to work with tools

Production
Hickory can be difficult to work, with cutting tools needing to be kept sharp due to the rapid blunting effect of the timber. It can be steam bent easily but can be difficult to glue, though it finishes and stains well.

Sustainability issues
This wood species is not listed in the CITES appendices of endangered species.

Key features
- Moderately high density: 835 kg/m^3 51 lbs/ft^3)
- Straight grained with a course texture
- Difficult to work
- Steam bends very well
- High bending strength
- High stiffness
- Very high shock resistance

Cost
Mid range, comparable with soft maple.

Typical applications
Hickory, like ash, is often used for handles due to its high bending strength, although hickory surpasses ash with one of the highest bending strengths and stiffness of any wood. It is used for baseball bats, hockey sticks and lacrosse sticks, tool handles for hammers and axes, the rungs of ladders and for drum sticks.

Sources
Most commercial grades of hickory come from the Eastern United States and South Eastern Canada.

Coconut Fibres *(Cocod nucifera)*

Have you ever seen an old armchair with seams that have come loose to reveal the rough, fibrous brown hair construction inside? If this sounds familiar, then either rubberized hair or coconut coir may have been the material used inside. Coconut, like bamboo, is becoming one of the beacons for the 'green' materials movement. Unlike bamboo and other plant-based materials, which are derived from the tree or trunk, it is not the palm tree itself but the fruit that is driving the area of greatest innovation. It's easy to see why; if you break open a fresh coconut you will see how well protected this seed is by the various layers that surround it, from the tough skin to the matted layer of coir that acts as a primitive bumper to stop the husk breaking when it falls from the tree. This multipurpose fruit has helped earn the palm tree a reputation as one of the most productive trees in the world, exploited mainly for its fruit but also for its trunk for producing timber, food and other products.

The hard husk of the coconut has been used in applications that exploit its hardness and durability; in some cases, it has been used to make small tiles for hard-wearing flooring. Perhaps more well known is the tangled, matted coir with its coarse, stiff, springy structure, that when dried out has been used in all manner of cushioning applications. According to Enkev, a supplier of fibres, coconut products have also been used to form packaging for eggs, perfume and luxury gifts.

Image: Cocolok® packaging by Enkev

+	−
–Good ventilation and sound insulation –Strong and tough –Extremely sustainable and compostable	–Coconut-fibres are flammable, so must be treated with a fire retardant for certain applications

Production
In order to get the most use out of the fibres they are washed, dried, curled by a spinning process and then fixed by steaming. They can then be processed in different ways including needling, which helps bind the fibres together. The fibres are also often combined with latex rubber to form sheets of various thicknesses that can be press-formed into 3D forms or die-cut into shapes.

Sustainability issues
Unlike many fruit-bearing trees, palm trees produce fruit at varying degrees of ripeness, providing 50 to 100 fruits per year.

Cost
As an agricultural waste product from the coconut oil industry it is not difficult to source. It can be used as cheaper alternative to building materials but, depending on application, prices vary.

Typical applications
This dense construction is based on a type of biomimicry, where the cushioning that the fibres give the coconut is applied to shoes, mattresses and upholstery. The fibres are also often covered with natural latex, which adds elasticity, for uses such as shoe soles and cushioning for upholstery. Other applications include packaging, ropes and scouring pads, and it is processed for food and oil. Also used as a natural-fibre reinforcement for concrete, insulation, doormats and brushes. Its swelling in water results in use in boats for plugging spaces between planks.

Key features
- Compostable
- Ventilates well due to its open structure
- Good sound insulation
- Good strength
- Very tough
- Waterproof, although fibres swell in water
- Relatively stiff and good in tension

Sources
India and Sri Lanka are the world's largest growers and exporters of coconut.

Tree Bark

The skin of a tree is an unlikely starting place for new materials, but as we cast an ever-widening net from which to harvest nature's ingredients we discover new ways of using existing materials, such as tree bark, in contemporary design. This spicy alternative to traditional woven textiles has a texture and crunchy feeling that lies somewhere between paper, leather and a piece of linen. With this type of material, the key to understanding it lies in the production, which is based on the same multilevel considerations as harvesting any natural product.

The bark used as a panel in these Vimaga shoes is by BarkTex® and is harvested from the inner bark of the Mutaba tree on eco-certified farms in Uganda. It is a raffia fleece without any additives, thereby consisting of pure cellulose. As might be expected, each piece is unique and hand-cultivated by a process similar to debarking a cork tree. Once chopped from the tree the bark is softened by boiling and then beaten with wooden mallets to stretch it and smooth the surface. After which it takes about a year for the tree to replenish its bark. BarkTex® produce a material of the same name and a Bark Cloth®, which undergoes additional processing.

Image: Bark Cloth® shoe by Vimaga

Production
The methods of cutting, fabrication and lamination are many and varied and the material should be considered for production in the same way as other textiles.

Sustainability issues
It is manufactured without any chemicals or agents and, according to the manufacturer, is 100% organic. They also stress that only under the right conditions of rain, sun and timing can debarking occur.

+	–
–Versatile –Tear resistant –Water resistant –100% organic and sustainable	–Comparatively expensive –Only available from specialist suppliers

Cost
Bark cloth® is approximately £21 per sq m ($38 per 10 sq ft) and an average single sheet cloth size is 2 x 3 metres ($6^1/_2$ x 10 ft). It is available in a variety of thickness, ranging from 0.5 mm to 2 mm.

Key features
- 100% organic
- Compelling consumer story
- Tear-resistant against the direction of the fibre
- Each piece is unique
- Abrasion and water resistant

Typical applications
Applications include fashion such as bags, shoes, hats, and blinds and wall coverings for interior design, also furniture and lighting. In other industries it is also used for trim and seating in car interiors and, interestingly, is also being experimented with for use as a fascia on consumer electronic products.

Sources
This particular material is harvested from certified farms in Uganda and sold by BarkTex®.

Horsehair

Body hair as a raw material for industrial and consumer applications is not as unusual as it might first seem; after all, it is one of nature's renewable materials. Consider also, that there are many varied types and uses of hair, such as badger-hair shaving brushes, horsehair paintbrushes and, of course, sheep's wool for yarn. Beyond this, there is also armchair upholstery, which, if you have ever seen an old one with seams that have come loose, reveal the fibrous brown horsehair construction inside.

Because there are ever more companies and reasons to search out natural, rapidly renewable materials, the exploration into materials such as hair goes into more and more depth. Hair is often combined with polymers that act as fillers, thus reducing the amount of virgin material used, and these fibrous materials generally have a limited capacity to be converted into three-dimensional forms. What strikes me about the form of rubberized animal hair used in armchairs is that this is a material usually seen underneath a bed mattress or inside a pair of shoes, showing that it has the potential to be used as a semi-structural material, wearing its matted, rubbery, fibrous qualities on its sleeve.

Hair has natural ventilation properties as well as being able to keep bodies warm. Horsehair in particular is very strong and its long fibres and surface structure enable it to transfer humidity away from the body.

Image: Hairlok® material by Enkev

+	–
–Good ventilation and sound insulation –Resists deterioration –Extremely sustainable and compostable	–Poor resistance to UV and to chemicals

Production
Horsehair goes through a similar process to coconut coir (see page 50) in order to get the most use out of the fibres, starting with washing, drying, curling by a spinning process, and then fixing by steaming. The fibres can then be processed in different ways, including needling, which helps bind the fibres together. Hair can be transformed using traditional fibre making techniques but it can also be mixed with resins including natural latex to provide cushioning in furniture. In these forms it is available as sheet material for die-cutting, punching, cutting, etc., or as loose fibres to be compression-moulded into three-dimensional forms.

Key features

- Compostable
- Good ventilation due to its open structure
- Good sound insulation
- Shock and vibration absorbing
- Resilient to deterioration
- Anti-static
- Sound and microwave absorbing
- Good hygroscopic properties
- Antimicrobial and breathable

Sources

As mentioned above, there are many forms of hair that can be sourced for and applied to industrial production, including badger hair. Hair can be moulded into various forms but can also be purchased as semi-formed sheets and blocks, from which components can be cut.

Sustainability issues

Clearly, this is a rapidly renewable product, and one that benefits from being harvested often.

Typical applications

Upholstery and soles for shoes. It is also marketed as an alternative to synthetic packaging materials for armrests, chairs and car seats. The shoemaker Camper is one of the many shoe companies to have exploited the material as an insole for shoes.

Cost

Moderately priced.

Cellulose

Cellulose is one of nature's ingredients that we have fully exploited, managing to identify, extract and apply it to many diverse uses. Unlike many of the materials featured in this book, it's not possible to provide a quick snapshot of the typical applications of cellulose; its uses are far too many, ranging from Korean craft papers to Shigeru Ban's architecture.

One of the main structural constituents of plant cellulose has been used as an ingredient to make plastics for ping-pong balls, plastic sunglasses, screwdriver handles, early film stock, fibres and textiles and, of course, paper in its many forms. Its use in all these areas is partly due to the fact that it reacts easily with other chemicals such as acetic and nitric acids, which when dissolved form acetates, such as cellulose acetate and nitrates such as cellulose nitrate.

One of my favourite stories about paper (one of the main products derived from cellulose) comes from Sri Lanka, where it is used as the basis for Elephant Poo Paper. This particular story encapsulates so much about the uses and fabrication of cellulose, which is based on regional ingredients, resources and culture. The interesting thing about the use of elephant dung to make paper is the fact that the animal's digestive system breaks down the fibres and softens them to provide the first stage of the paper making process. The high-tech LED light shown here is made from sandwiched paper sheets of DuraPulp.

Image: Lights by Claesson Koivisto Rune and Södra

+	–
–Huge variety of uses –Widely available	–Can be energy-intensive and use harmful chemicals in the production process (although companies such as Södra use no toxic chemicals)

Production
Where cellulose fibres are formed into a card-like material, the process is based on various methods, one of which involves press-forming together layers of paper that have been impregnated with PLA (polylactic acid), a biodegradable material made from maize starch or sugar cane. Heat and pressure combine to melt the PLA and bind all the layers of paper together to produce remarkably strong parts. The expected lifespan of the material is 3-4 years in heavy use, then biodegradable after that.

Sustainability issues
To make plastic from cellulose an alkaline solution of cellulose fibres – usually wood or cotton – known as viscose is extruded through a narrow slit into an acid bath. The acid regenerates the cellulose forming a film. Further treatment, such as washing and bleaching, yields cellophane. There are several ways of dealing with the shredded wood to obtain the pulp for paper making. One method is to bake it for several hours, at temperatures of 130-180°C (266-356°F, along with a chemical agent. In most cases, it is the use of the chemical treatments that is cause for environmental concern. Paper has one of the largest recycling streams of any material, however much of the recycled paper from Europe is sent on a boat halfway around the world to China. In addition, this brownish paper needs bleaching to reach a high whiteness, which is achieved by using magnesium oxide in addition to hydrogen peroxide and chlorine. The manufacture of virgin and recycled paper also uses large quantities of water.

Typical applications
Paper, compressed pulp, and for making circuit boards for use in the electronics industry. Paper is one of those materials that can be formed using an infinite number of possibilities. Apart from paper, textiles, including cotton and various forms of plastics, cellulose is also used as filler for plastics requiring a fine finish, for various uses in food, and as a thickener for latex paints, inks and cosmetics. It is also the basis for celluloid ping-pong balls, which are a mixture of nitrocellulose and camphor. PLA is safe for food products.

Sources
Cellulose is widely available.

Key features (Södra paper pulp)
- High stiffness – an alternative to plywood
- Economical material usage
- Card-making process is still to be fully commercialized
- No toxic chemicals
- Compelling consumer story

Derivatives
Cellulose such as Tencel® and Rayon® cellophane was originally developed by DuPont at the beginning of the twentieth century, but is now an Innovia Films brand. It is also the main subject in the Biocouture project featured in this book (see page 60).

Cost
Relatively inexpensive.

Silk *(from silk worms)*

Silk is a natural fibre that was first cultivated in Far East Asia more than 5,000 years ago, and formed one of the world's first global industries. From its origins at the heart of the silk route it has recently emerged as a renewable material with a lot of potential outside the garment industry. However, to understand the new potential of silk, beyond its traditional associations with glamour, one has to understand the basics of silk's properties. Starting as a less than glamorous protein excreted from the gland of the silkworm, which feeds on leaves of the mulberry tree, silk yields some incredible facts and statistics. First, and possibly most well known being silk's strength – it is the strongest natural fibre – and second, its ability to reflect light, which is a result of its triangular and prismatic section.

Beyond these well-known properties are a number of staggering discoveries that Professor Fiorenzo Omenetto from Tufts University in Massachusetts is exploring. Fiorenzo, who describes silk as 'a new old material' is looking at reverse engineering silk, taking it back to the liquid form as it exists in the gland of the silk worm to look at an amazing range of future opportunities. Silk from silkworms is not the only form of silk that is currently under the microscope of scientists. Spider silk, which was recently found to be a super heat conductor, and bee silk are also emerging as new materials.

Image: Silk cocoon

+	–
–Excellent strength –Superb optical qualities –Biocompatible –Sustainable	–Much of the research into new uses is still in development stages

Production
A single cocoon can yield enough fibre to produce up to 1,000 metres (328 feet) of thread. However, beyond the traditional forms of making silk garments, different methods of exploiting silk are being explored. The processing is dependent on the form the silk takes, which can be nanoparticles, sponges, films, fibres or solid blocks. A surprising number of fabrication techniques are being proposed, including 2D and 3D inkjet printing, electrospinning, optical lithography, moulding, micromachining with lasers and spin coating.

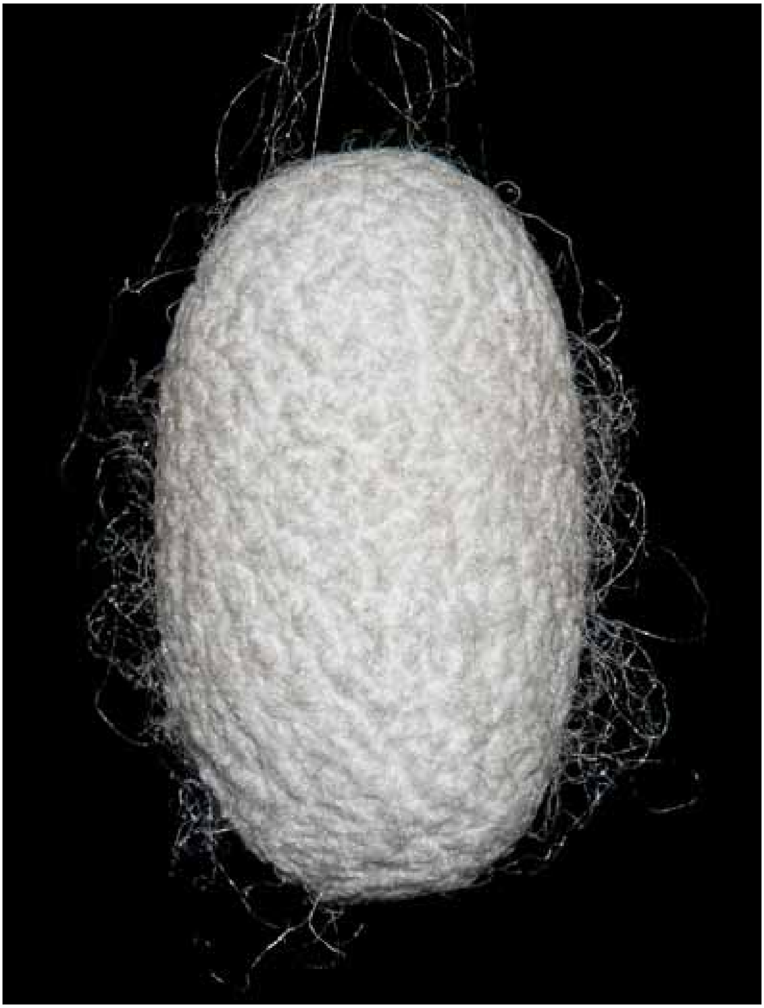
Sustainability issues
Silk is as 'green' as a material can get. Biodegradable, biocompatible and with a very high yield rate – the silk worm protects itself by wrapping a cocoon made from a single one kilometre (2/3 mile) fibre – it could be the truly 'new old material'.

Key features

- High strength-to-weight ratio
- Optical qualities
- Sustainable
- Biodegradable
- Biocompatible
- Low thermal conductivity
- Edible

Sources

China was at the heart of the silk route and continues to be the world's largest producer of silk, followed by India.



Typical applications

Apart from the obvious uses of woven silk and its origins in exotic textiles from Asia, Fiorenzo proposes that silk can be used for implanting into the body to replace veins and arteries, as implantable fibre optics used to store data through its optical properties, and for compostable products and sustainable plastics.

Cost

Fiorenzo's research is still in the development stage.

Bacterial Cellulose

OK, this is an unusual entry in a book about materials and design – after all, cellulose already appears several times in this book – but the reasons it is here are many. First, this particular case study highlights a completely new way in which designers are working with and looking at the formation of materials from which new products can be generated. In addition, it is a project instigated by a fashion designer, Suzanne Lee, who pioneered the use of bacterial cellulose as the basis for growing textiles. Finally, it is a discovery and application of a material that has deservedly gained much attention.

The jacket illustrated here is made from pure cellulose fibres but, unlike cellulose from plants (see the feature on cellulose, page 56), this cellulose was produced by bacteria grown in bathtubs of kombucha tea leaves. As the bacteria digest the sugar in the tea, they spin a layer of pure cellulose, which after two to three weeks – the length of time determines the thickness of the final material – results in a translucent skin, which can then be lifted from the bath, harvested and moulded into shape.

However, it's not just the story of the material that is harvested on the surface of a liquid that is compelling, but also the story of its instigation by a fashion designer rather than a chemist or engineer. I call Suzanne and her design associates 'new materialogists', a term that encapsulates a growing group of people from the creative industries who are developing new materials.

Image: BioCouture Jacket by Suzanne Lee

+	–
–Can be simultaneously grown and formed –Completely sustainable and non toxic	–Still in development so not commercially available –Not yet waterproof

Production
One of the key aspects of this project is that, unlike other forms of production, which involve a material being extracted, produced into fibres, granules, sheets, etc., and then formed through a separate process, BioCouture allows the material to be grown and formed in the same step.

Sustainability issues
Clearly this is a material and production proposal that has sustainability in its soul: It is an alternative to conventional, highly thirsty plants, such as cotton, is compostable and can even be grown from waste.

Typical applications
Suzanne Lee: 'One day it might be possible to produce bacterial cellulose in a huge array of different forms, feels and colours. In the future we could find ourselves surrounded by bacterial cellulose – in our clothes, our books and magazines, our cars, our buildings… the possibilities are almost endless!'

Key features
- Non-toxic
- Compostable
- Controlled thickness
- Fruit and vegetables used to create colour
- Antimicrobial
- No waste formed during production
- Single-step production
- Compelling consumer story
- Not currently waterproof

Cost/Sources
BioCouture is still in the developmental phase and not commercially available.

Bovine Leather

Without doubt leather is 'the' sensory material: it has a rich, warm and distinctive odour, a naturally and individually grained surface pattern, and it even makes a sound (creaks) when being broken in. There are lots of variables to be considered when choosing leather for different applications. Things like breeding, age and care of the animal are all factors: for example, young calves are less likely to have damaged skin due to bites or scratches. This means that large, single pieces of leather are generally more difficult to find in high quality due to the difficulty in finding older calves with undamaged skin. Other considerations include the skill of the individual removing the hide, where on the cow the leather comes from, the method of preservation and the skill and method of the tanner.

Specifying leather also requires an understanding of grades, cuts and types of cowhide. Top grain leather, as the name suggests, is the outside layer and offers the best quality. The first-split layer is below the top layer and offers less quality; the second-split layer, generally considered waste, follows this. Kid leather is made from the skin of young goats and, as you would imagine, is very soft with a fine texture.

Willem de Ridder's stools are made by fastening a leather sack around a mould and then boiling it. The leather tightens, and as it cools and hardens the mould is removed, leaving a construction that is strong enough to sit on.

Image: (Nothing to) Hide stool by Willem de Ridder

+	–
–Tough and water repellent –Huge range of uses –Enormous variety of finishes	–Can cause significant environmental impact

Production
The production of leather involves three main stages: skinning and preparation, tanning and finishing, often referred to as crusting. Various surface finishes can be applied to enhance the finish and consistency of the leather. Corrected grain leather is a process whereby an artificial grain is applied to a hide to achieve a consistent texture, something very commonly done in the automotive industry. There has also been a trend in contemporary design for reverence for leather to be rejected in favour of a more brutal approach, which sees the material boiled and stretched to achieve compelling forms and rigidity. Hand-stitching and brogueing are combined with industrial patent finishes, to explore how traditional techniques can be freed from the staid world of bespoke leather goods.

Cost
The cost varies vastly depending on labour costs for production, type and quality of leather, and the size of the hide in relation to imperfections. There is also the issue of waste owing to the awkward shape of a cow, which means that using a hide will result in lots of small, unusable offcuts.

Key features
- Rich associations
- Its characteristics are enhanced with age
- Water repellent
- Can provide a good grip

Typical applications
It might be easier to start where there aren't any typical applications. Leather is in everything from handbags to co-injection mouldings with plastics in luxury mobile phones.

Sustainability issues
The environmental impact of leather is huge. There are hazardous chemicals used in the tanning process and there is also the impact of livestock and effluents from the production. The de-hairing process uses caustic lime and the tanning process can also involve hazardous chemicals such as chromium. In relation to livestock, CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) regulates the use of leather to ensure that species are not endangered as a result of the trade in leather from exotic animals.

Sources
Widely available.

Fish Leather

The first thing to be clear about with fish leather is that it doesn't smell of fish. The world of material innovation is driven by many areas, one of which is the need to look for sustainable alternatives to existing, and rapidly dwindling, materials; this impacts on consumerism, with sustainable materials moving up the value chain in terms of consumer expectations. We all need to feel more caring, but the focus on eco materials is no longer about low-value goods, such as degradable plastic bags or stationery made from recycled paper; the new 'eco chic' demands that high-end goods, ranging from furniture to automotive industry products, incorporate ethically sourced and rapidly renewable materials.

Strength is one of the distinguishing features of fish leather, and is due to the cross-fibre structure – which is unlike bovine leather, in which the fibres run only in one direction. This natural cross-fibre pattern makes fish leather stronger than other leathers, when compared with the same thickness. According to one supplier three 1.75cm (½ in) strips of a particular fish's leather braided together can pull an automobile. Fish leather, as opposed to just plain fish skin, is distinguishable by curing with chemicals, known as tannins, which are added to the hide to preserve it and provide resistance to decay. The tanning process for fish leather is based on a multi-stage process, the first stage being to remove the fish oils and so eliminate the smell. This process also allows the leather to be strengthened.

Image: iPhone cover by Londine

+	–
–Water repellent –Strong and resistant to tearing –Easily processed –Utilizes a by-product of the fishing industry	–As with bovine leather, the tanning process of fish leather can involve harmful chemicals

Production
As with the production of bovine leather, production involves three main stages: the skinning and preparation, tanning and finishing. Fish leather can be processed in the same way as bovine leather.

Sustainability issues
As with bovine leather, CITES regulates the use of other leathers to ensure that species are not endangered as a result of the trade in leather from exotic animals. Obviously, fish leather should be sourced from certified sources, and fish should not be from an endangered species. None of the fish used for fish leather are on the endangered species list and, according to suppliers, are products from commercial fisheries.

Cost
Moderately priced.

Key features

- Comparatively high tensile strength
- Comparatively high resistance to tearing
- Water repellent
- Can provide a good grip
- Eco chic associations
- Breathable
- Characteristics are enhanced with age
- Compelling consumer story

Sources
Sourcing of fish comes from every corner of the planet, from both saltwater and freshwater.

Derivatives
Fish plastic.

Typical applications
Application areas are similar to those of bovine leather and range over everything from shoes to furniture.

Fish Scales

Erik de Laurens comes from the stable of what I refer to as 'new materialogists'. Like fashion designer Suzanne Lee with her BioCouture project, he comes from a design background and challenges the notion that material development and innovation should come purely from the science community. Not content with the use of oils, bones, meat and skin, Erik extracts even more value from fish by using the scales to create a new mouldable material.

'Fish Feast' was conceived while Erik was studying at the Royal College of Art, with the aim of exploring alternatives to globalization and the dependency we have on oil and therefore plastics. In his native Normandy, Erik discovered a company producing leather from fish skin, a by-product of the local fishing industry. In order to process the leather the fish is descaled, and it was this that gave Erik the idea of using this by-product of a by-product as a potential design opportunity.

Made of 100 per cent fish-scales, Fish Feast takes two average-sized salmon or 60 grams of dry fish scale to produce one beaker, as shown here. Its natural structure means that it is surprisingly strong and easy to dye in a range of colours. Eriks next aim is to develop further products and opportunities that can be used to sustain local fishing communities.

Image: The Fish Feast tumbler by Erik De Laurens

+	–
–Strong –Easy to dye –Attractive finish –Sustainable	–Not yet commercially available

Production
Compression moulding. Although scales vary enormously in size, shape and colour any type of fish scale can be used as long as the size of the scales exceeds around 5 mm (1/5 in) diameter.

Sustainability issues
This project goes beyond the green credentials of many materials of this type by being made from 100% fish scales, the by-product of a second-generation waste stream.

Typical applications
Apart from the beaker, Erik has explored glasses and proposes other non-durable and disposable items such as picnic products, which can be left on the ground to decompose after their use.

Key features
- Good strength
- Feels like plastic
- Doesn’t smell or feel like fish
- Dissolves in water
- Can be easily coloured
- Unique visual marble effect
- Compelling consumer story
- Compostable

Cost/Sources
The material is not currently available to buy commercially.

Algae

The vision of the future of materials perceived by scientists in the 1950s – that time of technological optimism – was always centred on the high-tech, and I am sure that few, if any, considered that a future material might be as dull as a simple organism like algae. However, in the future we may see algae farms based offshore to harvest oil from this plant, from which a new breed of plastic can be produced.

Over many years, French designer François Azambourg has produced some visionary experiments within the world of design. These range from explorations into alternative methods of constructing furniture to a new solution for packaging materials, which is based on algae, that he developed with Professor Donald Ingber of Harvard University. Algae are one of the newest raw materials that are being looked at as alternatives to petroleum-based plastics. In simple terms, algae is a seaweed, but this simple, highly abundant organism has incredibly diverse forms, running into hundreds of thousands of species.

Algae are a crucial plant type, which contribute a large amount of oxygen to the planet, apart from which it's also a great carbon dioxide muncher. Apart from its versatility and ability to grow in many environments, one of the reasons for algae's suitability as an alternative to traditional fuels and plastics is that it has an incredibly high growth rate.

Image: Bottle by François Azambourg

+	–
–Potential alternative to petroleum-based fuels and plastics –Biodegradable –Sustainable	–Still in development so not yet commercially available

Production
Details not available.

Sustainability issues
Unlike traditional plant-based plastics, many of which are derived from cornstarch, algae plastic would not affect food crops. Phytoplankton, one of the basics of algae, have declined substantially in the world's oceans over the past century.

Sources
As explained above, the major issue with algae is not its availability, as clearly this is a rapidly renewable plant abundantly available on the planet – it is generally found in shallow, fresh seawater and even waste water. But in fact, the worry is that it is going to disappear, not because of over-harvesting, as is the case with many natural materials, but as a result of its own natural depletion.

Cost/Sources
Still in the development stage.

Key features
The process of polymerization from algae is still in an exploratory phase; therefore, no tangible data regarding the properties of plastics produced from algae is currently available.

Typical applications
Apart from its potential applications as a biofuel, and to replace petroleum-based products, its more common application is as a food, which takes a number of forms depending on the culture using it, such as nori in Japan, or as a lettuce in parts of Europe. Algae have many other applications, which include their use as a pigment in natural dyes, and as a treatment for sewage, replacing artificial and potentially harmful chemicals. It has also been used as a fertilizer and as a source of biofuel.

Protein

It's estimated than in one company alone in North America six million chickens are killed daily to supply the food industry. This demonstrates the scale of mass-consumption and the waste that this industry generates. As we look to sustainable alternatives to petrochemicals to produce what we currently know as plastic, so we must look to the waste that comes from industry as a potential source to make these materials. At present there are four main groups of bioplastic: starch derived, plant-oil derived, fermentation of monomer, and protein derived.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) in the Australian state of Victoria is exploring ways to turn the chicken feathers from this vast amount of waste into plastic. The main ingredient that researchers are extracting is protein from which to create plastic. This is not a new concept: some of the earliest plastics were derived from proteins in milk called casein, and the blood from cows was used to make another early plastic.

The particular protein that exists in feathers is called keratin, a protein that adds strength to hair and fingernails. The process works by breaking down the feathers into small pieces and using heat to break down the proteins and then link them together in a 'polymerization' process, forming longer chains and a rigid structure.

Image: Chicken feathers

+	–
–Potential alternative to petrochemical-based plastics –Biodegradable –Utilizes waste from the food industry	–Brittle –Not yet commercially available

Production
Early tests have shown that vacuum forming, extrusion, compression moulding, injection moulding and blow moulding are all potential methods of forming this material.

Sustainability issues
Animal proteins are subject to stiff regulations. Beef producers took an economic hit when by-products such as blood and bone were regulated out of the rendering process after BSE was found in Canada, for fear the material contained deadly prions, infectious proteins that cause BSE, more commonly known as mad cow disease.

Typical applications
Feather-based plastic could be used for all kinds of products, from plastic cups and plates to furniture. In addition to making use of feathers that would otherwise end up in landfills, it is highly biodegradable.

Key features
- Alternative to petrochemical-based plastics
- Transparent
- Brittle
- Biodegradable

Cost/Sources
The material is not currently commercially available, it is still in development.

Cork

When science fiction writers of the 1960s envisaged the future they probably didn't bargain on cork, which is extracted from bark and has been used for thousands of years, still occupying a strong position as a high-tech material in the early part of the twenty-first century. Incredibly, this tree peel has been used in space shuttles due to its thermal insulation properties; it protects the fuel tanks on re-entry into the Earth's atmosphere, a function that is the result of 1 cm (3/8 in) of cork containing 40,000,000 cells of air.

In our intensive investigation and our ingenuity in forming new materials we are ultimately attempting to emulate nature. Cork is one of the many natural and rapidly renewable resources that have become prominent in the world of 'new materials'. It is also a material that, depending on where it is used, has many associations. For example, cork products might bring to mind English garden fêtes and Christmas bazaars; these festivals of community making often feature place mats and pin boards and other traditional cork products. But if we examine cork without any of its traditional associations we see it for what it is, a material that is renewable, natural, very light and impermeable to water. A material that feels like a chewable, warm, dense natural sponge, and one of the few materials that has Poisson ratio of 0, which in simple terms means that it does not get thinner when stretched, unlike most other springy materials.

Image: Jasper Morrison cork furniture for Vitra

+	–
–Versatile –Good strength-to-weight ratio –Water resistant –Biodegradable	–Can suffer from dated, cut-price associations

Production
In terms of production, cork can be machined, routed, lathe-worked, cut using similar techniques to woodworking, and can be formed using a process similar to compression-moulding plastics. It can be turned into a sheet, woven as a textile and even combined with other flecks of different types of cork to make a decorative composite.

Sustainability issues
Cork trees absorb up to five times more CO_2 than other trees, while producing a new harvest of cork bark every nine years. Each mature cork tree produces enough cork bark to make 4,000 bottle stoppers every nine years. The harvesting of cork takes place in the summer when the bark expands and naturally comes away from the inner layer of the tree.

Cost
Relatively inexpensive.

Typical applications
As the Portuguese cork industry suffers as a result of corks in wine bottles being replaced with screw tops, the industry has looked to other areas of application. Apart from place mats and craft-fair archetypes, cork is also used for dartboards, shoe liners, anti-vibration pads, handles for sporting goods such as fishing rods, floats and, of course, contemporary furniture. One of the biggest areas of application is in cork fabrics, which offer a huge range of colours, effects and finishes, that are being used in fashion accessories like handbags and even as an upholstery material. It has even been used as a postage stamp in Portugal. One of the interesting qualities of cork trees is their ability to withstand fires; as a result they are planted to act as fire barriers.

Key features
- Poisson ratio of 0
- Renewable
- Biodegradable
- Elastic
- Vibration dampening
- Shock dampening
- Impermeable to liquids
- Impermeable to gases
- Good heat insulation

Sources
Portugal is one of the world's biggest exporters of cork and accounts for 60% of the world's production, producing over 300,000 tonnes a year. Spain, Algeria and Morocco are also large producers.

Bamboo *(Bambusoideae)*

Bamboo has over recent years generated so much attention that it might be perceived as *the* material for the 21st century, a beacon of sustainability, and a material so overused to sell the 'green' movement that we are led to believe that anything made from bamboo must be eco-friendly.

Bamboo is nature's lightest-weight material, the result of being the fastest-growing plant in the world, with some species of this grass growing by 1 meter (3 feet) per day. It is a material that, in the right climate, you can grow virtually on your doorstep (potentially leading to low transportation costs), can be used to construct a building within five years of planting, and will continue to grow after it has been harvested. With its excellent strength-to-weight ratio, it can be split into strips, which can be woven into baskets and furniture and, with nutritional, medicinal and structural properties it's the ideal material for when you are stranded on a desert island.

Bamboo has been used in tropical and subtropical countries for centuries, with the skills of harvesting and construction being passed down for hundreds of years. With around 75 species it is another material that, if humans had invented it, would be heralded as a wonder material, up there with Teflon and Velcro. In contemporary design and architecture, the unique qualities of this natural material provide a rich source from which new uses are constantly being sought.

Image: Bambu Table by Henry Tjearby for Artek

+	–
–Low cost –Light and strong –Extremely elastic –Multitude of uses –Rapidly renewable	–Care must be taken to ensure it is responsibly sourced and processed

Production
The many uses of bamboo are a result of the ability of its fibres to be split and shredded. Beyond conventional pole structures, these fibres are also used in making textiles. As with trees and timbers, the exact properties of a piece of bamboo will depend on where the material is taken from in relation to the growth ring.

Sustainability issues
It is a self-regenerating raw material. In contrast to harvesting wood from trees, which leads to intensive reforestation, bamboo regrows as soon as it has been harvested. It is over two and half times more cost efficient to convert to building materials than traditional wood and more than 50 times cheaper than steel. Author and sustainability entrepreneur Gunter Pauli claims of bamboo that: 'on 500 square metres (5381 square feet) of land you can harvest a house each year'.

Cost
Relatively inexpensive.

Key features
- 300–400 kg/m^3 (18–25 lbs/ft^3)
- Rapidly renewable
- Excellent strength-to-weight ratio
- Low energy processing
- Versatile processing
- Good flexing

Sources
Most of the harvesting of bamboo takes place in tropical South Asia and South East Asia.

Typical applications
The use of bamboo as a material is growing almost as fast as the plant itself. It has a huge variety of uses: musical instruments, shelter, architecture, flooring, scaffolding, roofing, medicine, cellulose, paper, bridges, baskets, furniture, bamboo plywood, and wind protection in farming. In Hong Kong it is used for scaffolding for buildings as high as 70 storeys due to it being more flexible than steel and able to flex in high winds. In the aftermath of typhoons in Asia steel scaffolding has collapsed while bamboo is still standing. Its fibres can be shredded and converted into fibres to make textiles.

Rattan *(Calamus rotang)*

Rattan evokes tropical climates and hand-crafted outdoor furniture. There are over 600 species of rattan, a vine-like climbing plant that is characterized by its slender, long and flexible stems. Rattan is in fact the plant with the world's longest stems, reaching up to 200 metres (656 feet). It is the length and strength of these stems that is exploited by weaving rattan into its many applications, the most notable of which being domestic furniture.

The vine is derived from the palm of the fast-growing *Calamus rotang* plant. The stems are stripped of their skin and this skin is used for weaving. The stems are subsequently left to cure in the sun and, depending on the species and thickness of the vine, these go through a number of steps before being formed into furniture. The inherent toughness, flexibility, strength, light weight and durability of rattan can be appreciated through its prolific use in furniture and basket making.

It is estimated that around 600,000 tonnes of rattan is exported each year from Indonesia alone, around 80% of the total world market. However, due to its importance on the Indonesian economy as a local commodity, it has generated political debate with the Indonesian government banning the export of unprocessed rattan at the beginning of 2012. By doing so it hoped – without success – to boost the domestic manufacturing industry.

Image: Rattan and plastic basket by Cordula Kehrer

+	–
–Strong and tough –Extremely flexible –Good resistance to splitting	–Some species are endangered due to over farming

Production
Due to the flexibility of the long fibres, he most common form of processing rattan is weaving. Woven rattan is taken from the skin that is usually peeled from the stalk. The remaining 'core' of the rattan can also be used in furniture making. The various species of rattan canes range in thickness from 2 mm up to 40 mm (1/8 in to 1 1/2 in) in diameter. The larger diameter canes also stain and finish well and are often buffed to produce a polished surface.

Sustainability issues
Over-cutting rattan slows or stops the regeneration process and although it is often perceived as being a 'green' material many species of rattan are now endangered due to over farming – consequently affecting wildlife. As a result, plantations are being established to create a more managed harvesting, evident in a 26% drop in global trade between 2006 and 2008 due to dwindling resources and forest loss.

Key features
- Relatively lightweight
- Rapidly renewable
- Very tough
- Good flexing strength with resistance to splitting
- Durable

Sources
Most of the world's rattan comes from Indonesia. The rest of the world's supply comes from the Philippines, Sri Lanka, Malaysia and Bangladesh. As with any natural material there are grades of rattan based on colour and flexing as opposed to brittle properties.

Typical applications
Beyond furniture rattan is used for baskets, umbrella handles, door mats, and structural applications for interior and exterior products. Thinner canes are used in the production of rope and twine, which also includes rope bridges. Although now antiquated in the West, its strength and flexibility made it a highly effective cane. More unusual applications come in the form of research that has been undertaken into turning rattan into a replacement for bones. Through a chemical process Italian scientists have managed to implant this 'rattan bone' into sheep.

Cost
Due to the changing levels of harvesting the price fluctuates. The mid 1990s saw rattan reach a high of around £2.50 ($3.90) per kg.

Hemp

It is interesting to observe how different carmakers approach the issue of sustainability. In Germany, for example, BMW focuses on high-tech materials as a response to weight-reduction, while Mercedes might focus on plant fibres in a range of applications for items such as interior panels. In most of these cases, these materials are used in composites and are hidden in surprising applications not visible to consumers. For example, when you step into a Mercedes car you don't see evidence of natural fibres everywhere; you don't see hemp or coconut fibres in door panels. It's still an environment where shiny surfaces or sumptuous leather equal luxury. However, the use of plant-based fibres in composites – such as carrot fibres (see page 82) – is clearly a big trend, a market that will continue to grow and one that the automotive industry will continue to invest in. It remains to be seen how the luxury aesthetic in high-end cars will embrace this more 'crunchy' appeal.

Hemp is a major area of development within the plant fibre industry, owing to its strength, overall abundance and also the fact that, as a plant, hemp is a pollution muncher. However, the idea of plant-based fibres such as hemp being used in cars is not a new one. Henry Ford experimented with hemp composites for body panels in the early twentieth century as part of a PR exercise that was famously captured in a photograph of him swinging a sledgehammer at one of his cars to validate its strength.

Image: Aisslinger Chair

+	–
–Good strength-to-weight ratio –Durable –High thermal conductivity –Sustainable	–On its own it has a very coarse texture

Production
Hemp fibres are separated from the stiff inner stick by a process called retting, where the thin hemp fibres are soaked to soften them and removed from this hard core. These fibres produce longer fibres than that of the flax plant and are much coarser. The many varied ways in which hemp fibres can be applied to industrial products means that there are a multitude of uses that the fibres can be processed for.

Sustainability issues
Hemp has many environmental advantages. It is versatile in relation to the agricultural land it can be grown on, and the hemp plant is also a pollution muncher, drawing CO_2 from the atmosphere and so providing a benefit for the planet. It is estimated that every tonne of industrial hemp stems contains 0.445 tonnes of carbon absorbed from the atmosphere.

Cost
Hemp is relatively inexpensive to source but price varies depending on where it is implemented and in what industry.

Derivatives
Kirei Canamo particle board.

Typical applications
Hemp is used for coarse fabrics or it is blended with other fibres, such as linen and cotton, for clothing. The length and strength of the fibres also results in its use in fibre construction boards, ropes and composite fibres. At one point it was of such strategic value that it was mandatory for American citizens to grow hemp plants for use in rope and sailcloth. Smaller fibres are also combined with plastics to create what are sometimes known as 'plastic woods'. Due to its high thermal conductivity it is also used in clothing.

Key features
- Relatively lightweight
- High strength-to-weight ratio
- Long, hollow fibres
- Stronger and more durable than cotton
- Coarse
- High resistance to bacteria
- High thermal conductivity
- Biodegradable
- Antimicrobial properties
- Compelling consumer story

Sources
Most hemp production takes place in China, although it is grown in many other countries.

Wheat Straw

The timber industry is crammed with examples of waste materials being reclaimed to form new composites for building and interior applications. Materials like MDF, particle board and OS board (orientated-strand board) all use the by-products from various forms of wood production. There are also materials like Paralam® and Glulam® that combine resins with small strands of timber to create strong, stiff, dimensionally stable beams for use in construction. However, although these materials reuse waste materials, a common problem with many of them is the use of harmful formaldehydes as the binding resins.

One particular company has gone a step further in providing a truly green product, reclaiming alternative, rapidly sustainable materials and using less harmful binders to develop a range of sheet materials that use tree-free, agriculturally based and environmentally friendly wheat straw and sunflower hulls combined with a resin that is formaldehyde free. The company, Kirei, are US-based and produce environmentally neutral and beneficial alternatives to traditional panel products and building materials. Among their products are Kirei Board™ and Wheatboard™, which use a combination of wheat straw and sorghum grass. The significance of this blended panel product is that it demonstrates the increasing focus on agricultural industry to replace not only wood but also polymers in industrial production.

Image: Wheatboard™ by Kirei

+	–
–Lightweight and hard –Easy to work –Moisture resistant –VOC free –Renewable	–Not attractive so suited to interior panel use mainly

Production
It machines and finishes well and is workable in the same way as more conventional materials but with reduced tool wear. It is also available in a range of sheet sizes and thickness.

Sustainability issues
The manufacturers of Wheatboard™ state that it utilizes the waste part of the wheat, after the edible portion of the plant has been harvested, which would otherwise have been put in landfills. It also does not use urea-formaldehyde or release any volatile organic compounds –VOCs – into the atmosphere.

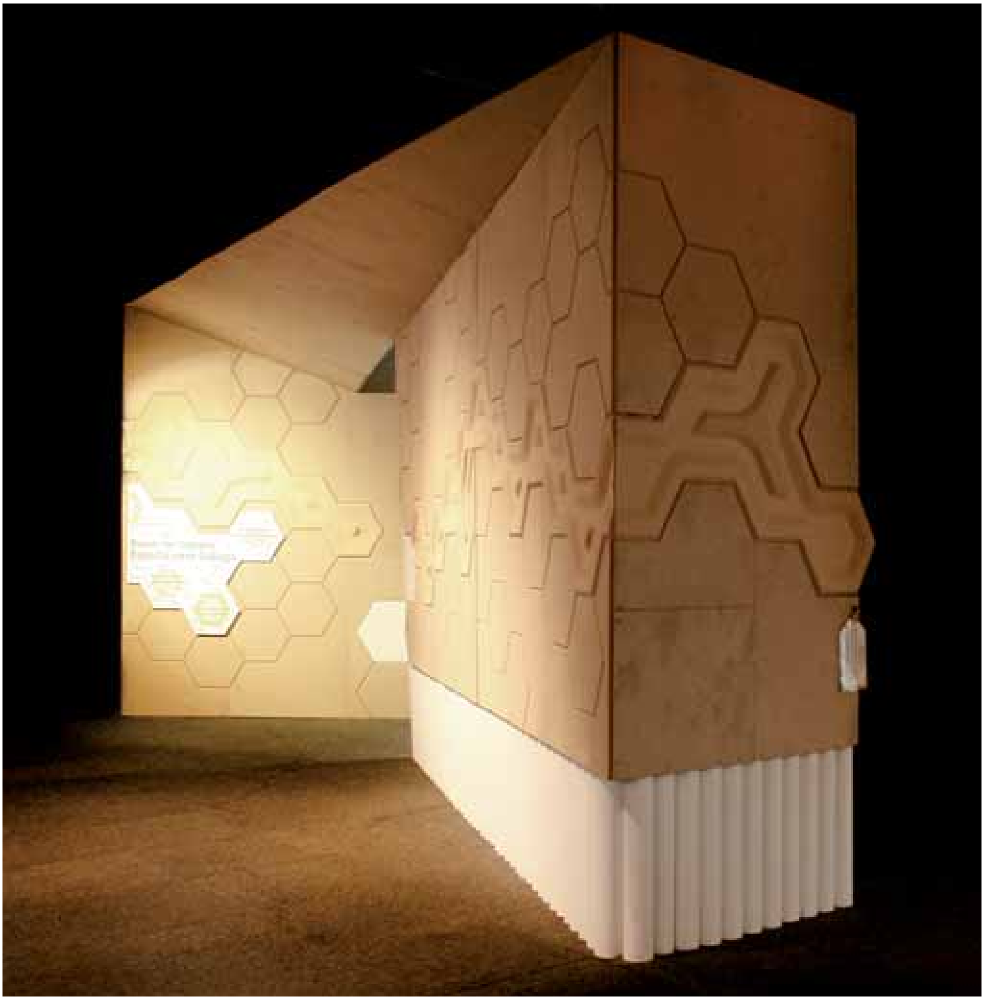
Sources
This product is available from US-based Kirei.

Key features

- Comparatively lightweight
- Rapidly renewable
- Emission-free resins
- Good surface hardness
- Good moisture resistance

Cost

Kirei retails 13 mm (1/2 in) or 2 cm (3/4 in) thick x 1.2 m x 2.4 m (4 ft x 8 ft) sheets starting at £50 (US $80).



Typical applications

Wheatboard™ is an interior panel product that has all the typical applications you would expect from this kind of material. Existing environments and applications include schools, museums, hospitals, retirement homes, laboratories, libraries and other public buildings. It can also be used in non-structural interior applications including general woodworking, cabinets, wall and partition panelling, work surfaces and office furniture.

Carrot Fibres

Composites are often perceived as being advanced materials, as many were developed for aerospace, military or formula one racing. This association is also partly based on the distinctive herringbone pattern and appearance of composites such as carbon fibre, which have become part of the modern family of luxury materials. But can a composite made up of carrot fibres still be considered an advanced material?

More and more plants are becoming valuable sources of material innovation: starch from corn and potato skins, hemp fibres, castor oil, bark and algae are some of the plant products that are driving development of new materials. However, the applications of these materials are no longer being perceived as rural, and are instead leading to radical new innovations in the world of advanced composites. The main innovation here is the use of a rapidly renewable source of fibres from carrots and other root vegetables in comparison to oil, which is used to produce carbon fibres. However, around 20 per cent oil is still needed in what is branded as Curran® to complement the 80 per cent carrot fibres.

Dr David Hepworth and Dr Eric Whale produced Curran® to utilize nanofibres extracted from root vegetables. The process involves mechanically breaking down carrots into tiny particles to form a slurry. The fibres are then extracted and formed into various states from which parts can be moulded, or coatings of Curran® can be applied or mixed with other resins.

Image: The Reactor™ fishing rod, made from Curran® and carbon fibre

+	–
–High strength-to-weight-ratio –Tough –Good stiffness –Sustainable	–Currently only available from limited suppliers

Production
Curran® in its primary state comes out as a paste (similar to mashed potatoes). The paste has 93% water and 7% cellulose fibres and can be mixed with different polymers. Because Curran® is in a semi-liquid state it is very easy to use the material by mixing it with paints, coatings and resins, and it is compatible with a multitude of conventional resins, such as epoxy, polyurethane and polyester. It is also available as a powder, as sheets, and as a loose matting.

Sustainability issues
Curran® is produced from the carrot waste discarded in the food industry, therefore it does not compete for land with crops for food.

Key features

- Low temperature production
- Based on a renewable resource
- High strength-to-weight ratio
- Outstanding toughness
- Outstanding stiffness
- Compelling consumer story

Sources

At present, the technology is limited to UK-based CelluComp.

Typical applications

One of the applications that CelluComp is exploring for Curran® is as an additive for paints and coatings, where it would work as a thickener and also enhance the mechanical properties. Shredded Curran® sheets can be used as a loose matting to put into 3D moulds and pieces can be made using vacuum moulding or resin transfer moulding. In paste form, Curran® can be dried into thin sheets and then used as laminates for the construction of solid panels, for layers in skis or skate boards, or on the outside of core materials such as foam. These sheets are 85% cellulose fibre and 15% resin, so a very high percentage of randomly-orientated fibre is in the final product and the mechanical properties are impressive.

Cost

According to CelluComp, the main costs are in the process used to produce the composite itself, rather than the actual fibres, which in relation to carbon or glass fibres are still very low cost.

Mycelium

Fast growing, low water consumption, compostable and a material that does not take anything out of the planet that can't be put back; this sounds like a miracle material that could potentially make plastic packing foams redundant. Evocative is a company formed by a group of designers who have found potential in mycelium, a fungal network of threadlike cells that is formed in the roots of a mushroom, to replace conventional plastic foams.

As with bacterial cellulose, one step in the chain of production of this material is removed because it is grown and formed directly into the shape in which it is needed. The product, called EcoCradle®, is grown in the dark at the very fast rate of between five and seven days, with no need for water or petrochemical inputs. Once grown, the material has properties similar to expanded plastic foam, also with a similar cost. The material is acoustic, thermal and shock insulating, as well as being Class 1 fire retardant. This innovation has resulted in a completely new type of foam product. It was invented on the premise that traditional packing foams are made from oil/plastics that take more than 65 million years to form and are mainly used in a product that has a very short lifespan.

EcoCradle® is soft and about as strong as low-density expanded polystyrene foams, but not as durable; however, when it is combined with other materials this is not the case.

Image: EcoCradle® packaging

+	–
–Inexpensive –Good shock absorbency and insulation –Excellent alternative to plastic packaging –100% sustainable	–Limited manufacturing options –Limited availability

Production
Because it is grown rather than manufactured, there are limited options available for processing this material; however, almost any shape can be 'grown' into a mould in about a week. Due to Ecovative's unusual production technique, this material may be best suited to bold shapes. The thinnest walls that can currently be produced are approximately 13 mm (1/2 in), although they are currently working on creating a material that is much thinner.

Sustainability issues
EcoCradle® has sustainability at its heart and is the direct result of looking at ways to reduce waste and reduce the use of plastics. It is fully biodegradable but it takes soil biota and long-term exposure to water to trigger natural biodegradation. EcoCradle® provides an excellent alternative to traditional packaging materials or applications where a lightweight composite is required. EcoCradle® can be used to make disposable products of considerable size

Cost
The cost of EcoCradle® is comparable to, or even cheaper than, expanded polystyrene foams. These include insulation blocks and acoustics tiles for buildings, as well as candles and herb planters, and many traditional plastic foam applications in cars.

Sources
Limited to a single supplier.

Typical applications
The Ecovative website suggests a range of applications that range well beyond packaging.

Key features
- Lightweight
- Naturally fire retardant
- Cushioning
- Low cost
- Good insulation properties
- Shock absorbent
- Low water consumption
- Rapidly renewable
- Compelling consumer story
- Biodegradable
- Carbon neutral

Sugarcane

Sugar is the evaporated and crystallized extract from the stalk of the sugarcane plant and, although it is an important source of bio fuels, it is not a material one would think of as the starting point for a product design. Designer Emiliano Godoy, however, saw it as an opportunity based on several characteristics of one of its by-products: sugar. Godoy first noticed sugar's potential as a material for making impermanent products in 2003, when studying at Brooklyn's Pratt Institute. Godoy, who grew up in Mexico City, found inspiration in the traditional Mexican confection called *calaverita de azucar* to conjure up his thesis project, Sweet Disposable.

The calaverita, a skull made entirely of sugar, is created to celebrate the Mexican Day of the Dead. Sugar, cream of tartar, and just enough water to achieve the consistency of wet sand are moulded into skull shapes, which are then left out as offerings to the deceased. Godoy linked this rite to an idea of more recent vintage: the cradle-to-cradle thinking of green gurus William McDonough and Michael Braungart. The products Godoy created – a golf tee,skeet targets, a votive holder and a lamp, among others – are made almost entirely of sugar, so that when disposed of the sugar returns to the earth as a 'biological nutrient'. This also makes waste storage systems unnecessary, which, considering the resources required for recycling bins and processing plants, can actually be wasteful themselves.

Image: Emiliano Godoy's Sweet Disposables skeet targets

+	–
–Versatile –Abundantly available –100% biodegradable	–Short lifespan

Production
The stalks (cane) of the plant are crushed to extract the juice, which is then concentrated by boiling, crystallized and clarified. Godoy's products are made by a form of compression moulding.

Sustainability issues
This scenario demonstrates the possibility of eliminating the need for reclamation and waste storage. By proposing both durable and non-durable products with a 100% biodegradable material, the disposal of the product is taken into the realm of design: every product will be eventually discarded. The sugarcane is also one of the plants with the highest bio diversion efficiency, providing a valuable source of biofuel, and bagasse fibres are also used in furniture.

Typical applications
The main use of sugarcane is for sucrose, but several other commodities are derived. One very usable material from a designer's perspective is bagasse, which is the residual and woody fibre in the cane and is used for pulp and paper products. Of increasing importance is ethanol, a by-product of sugar production and one of the main biofuels.

Key features
- Abundant
- Rapidly replenishable
- Compostable
- Short life span

Sources
The plant is grown on plantations in Cuba, Indonesia, South America, Hawaii and some southern states of the US. According to the Food And Agriculture Organization Of The United Nations, sugarcane is the world's largest crop with production in 2011 estimated at around 734,006,000 tonnes in Brazil alone (the world's largest producer). To give an idea of this scale, orange production in Brazil (again the world's largest producer) was 19,000,000 tonnes for the same year.

Cost
Relatively inexpensive.

Orange Peel

This by-product of the fruit juice industry is a renewable and compostable material. As many other case studies in this book have demonstrated, designers are turning uncommon waste and biomaterials into manufacturable new forms using design creativity and experimentation to produce new recipes for materials from natural ingredients. Suzanne Lee is one such example with her BioCouture projects, and APeel – by Alkesh Parmar – is another.

Parmar has taken the rind, pith and seed waste from the orange juice industry and transformed it into a viable mouldable, rigid material. And a huge amount of waste it is: according to the Food And Agriculture Organization of the United Nations, Brazil accounts for the largest production of oranges in the world. In 2011 its total production was in the region of 19,000,000 tonnes and, if we estimate that around a third is used for processing – then that's about 95,000,000,000 tonnes of waste from Brazil alone.

APeel is a 100% sustainable material that uses only natural, organic binders – no resins and synthetic binders have been added. Is also conceived to create a material that uses the least amount of water, energy and economical manufacturing methods. Hard or flexible, depending on the exact type of ingredients, APeel uses the dried rind as the particles that give the material its course texture, and pectin, found in the rind, as a binder. In case you are wondering, it does have a citrus fragrance, but only when you give it a gentle rub.

Image: APeel by Alkesh Parmar

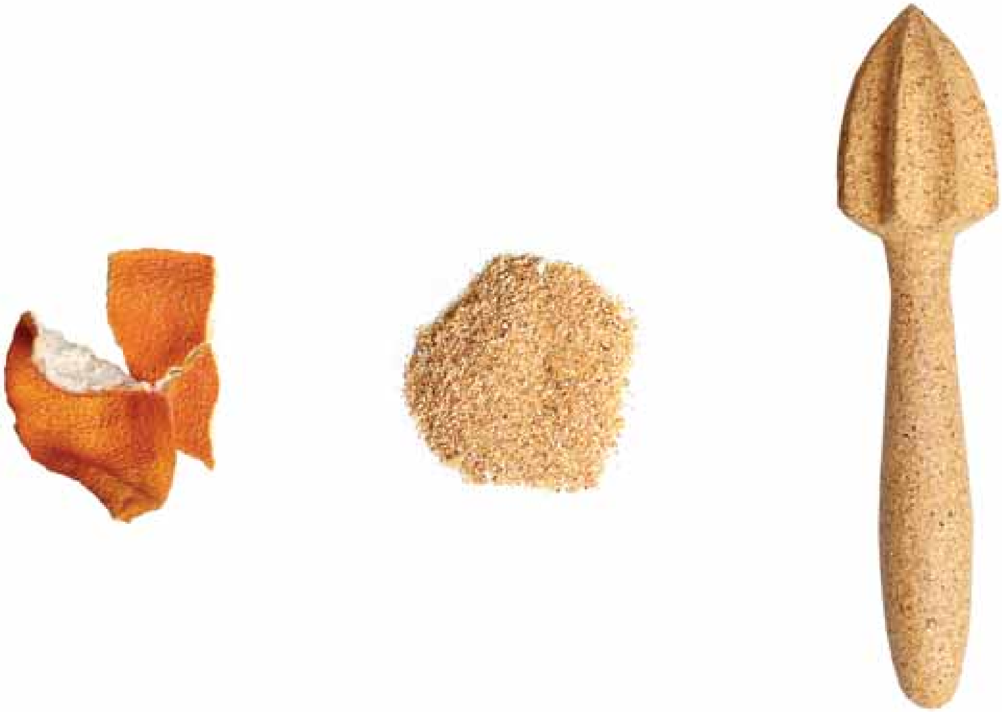
+	–
–Versatile production –Uses up waste from the food industry –100% sustainable	–Year-round supply is a challenge.

Production
APeel can be compression moulded, cast, extruded and – if formed in a sheet – can be laser cut and machined on standard woodworking machines. Alkesh is also currently exploring the idea of rapid 3D printing with the material.

Sustainability issues
According to Alkesh there is around 15.6 million metric tonnes of citrus waste per year that can be converted into a new material. Where the use of food crops as the source for materials is often berated for removing a source of food, APeel uses only the by-product, which ordinarily has no use. As a fruit, oranges are seasonal and therefore create a challenge for year round supply.

Key features
- High strength
- Good thermal conductor
- Good sound absorption properties
- Compostable
- High density
- Odour neutralizing
- Watertight for limited periods of time

Sources
Oranges are grown in tropical and subtropical climates, with Brazil being by far the largest producer. APeel also has the potential to become a 'local' material in the hot climates that can sustain orange growth.



Typical applications
Alkesh is currently proposing APeel as an alternative to MDF for the construction industry and as a material for prototyping. Other applications include heels for footwear, to replace polyurethane, and as insoles as a natural odour neutralizer. In addition, it is being considered for cosmetic packaging, plant pots, egg cartons and fruit trays for packaging.

Cost
It is difficult to give precise costs, but when compared with card-type materials it can be cheaper. And apart from being a sustainable alternative to MDF it also offers a comparable cost.

PLA *(Polylactic Acid)*

Along with nanotechnologies, smart materials and composites, green plastics are one of the fastest growing families of materials. The plastics industry is full of examples of green plastics that wear their recycling credentials on their sleeves, such as the materials icon that is Smile Plastics. This UK-based company were one of the first in the world to see the opportunities for producing upcycled plastic sheets by reusing discarded yogurt pots, wellington boots and mobile phone cases. Big industry, global petrochemical companies are also well underway in their explorations of renewable sources from which to make plastics. As a result, there has been a surge in the use of a range of the renewables from which plastics can be produced.

One of the first and most popular raw ingredients used for green plastics is polylactic acid (PLA), a technology based on a method of extracting the carbon from plants, which the plants, in turn, have removed from the air through photosynthesis. Carbon is stored in plant starches, which can be broken down into natural plant sugars. The carbon and other elements are then used to make PLA.

Once the corn, sugar cane or other starch-based plant source has been milled the starch is separated from the raw material. From this starch unrefined dextrose is produced. The dextrose is then turned into lactic acid through fermentation, similar to that used for making wine and beer.

Image: Noisezero bioplastic headphones, Michael Young

+	–
–Versatile production –Good clarity –Good stiffness –Compostable	–Expensive compared to petroleum-based plastics –Low durability

Production
PLAs can be processed using a range of standard plastic forming techniques, including foaming extrusion, injection moulding, thermoforming and calendaring.

Sustainability issues
PLAs are biodegradable and compostable releasing 60% less greenhouse gases and using 50% less non-renewable energy than traditional plastics, such as PET and PS. The main issues with this first generation of bioplastics are the use of foodstock and land as the raw material.

Cost
These materials are still not economically competitive with petroleum-based plastics.

Sources
The raw material from which PLA is extracted includes potatoes, corn and sugar cane. Widely available from multiple suppliers under multiple brand names.

Derivatives
PLA can be modified for a variety of applications, such as fibres, foams, emulsions and chemical intermediaries.

Key features
- Annually renewable
- Low odour
- Compostable
- Good clarity
- Good stiffness
- Good surface finish
- Low durability

Typical applications
Credit cards, blow-moulded water bottles, casing for various consumer electronics, water-based emulsions, clothing, carpet tiles, rigid and flexible films for thermoformed food and beverage containers.

Castor Oil

When does plastic stop being plastic? Ezio Manzini, a sustainable design strategist, likens the rapid evolution of materials and trying to define these materials as 'like trying to capture a family photograph when the whole family is in constant motion.' On this basis, at what point does the definition of plastic, as a substance derived from petroleum, no longer fit with the ever-increasing range of alternative starting points and ingredients that are being developed? How far will this definition stretch when in the near future plastic may be derived from any number of raw materials, which currently range from starch to chicken feathers and now castor oil?

As the world looks beyond petrochemicals to create plastic products, one of the sources it is looking to is castor oil, a substance that in popular knowledge is thought of as a laxative. Castor oil is a viscous liquid extracted from the seeds of the castor plant and is one of the most widely used vegetable oils. It was not so long ago that bioplastics were associated with flimsy, throwaway items like disposable cutlery and packaging, but renewable plastics have a come a long way in a short time. The sunglasses shown here, from Smith Optics, use Rilsan® Clear Renew, a high-performance, optical-grade plastic from the French supplier Arkema. They are made entirely with biodegradable and renewable castor oil but with the properties of nylon, meaning that it is tough with good impact resistance.

Image: Evolve sunglasses by Smith Optics

+	–
–Versatile production –Strong –Good resistance to wear and tear –Low friction	–Can be environmentally hazardous to grow and manufacture –Poor chemical resistance

Production
This renewable polyamide – Nylon – is easy to process using conventional thermoplastic techniques, including injection moulding, blow moulding, rotational moulding and extrusion. It can also be enhanced with countless fillers, such as glass and various colourants. It can also be extruded into a tough fibre for textile applications.

Sustainability issues
The wide usage of castor oil conflicts with the castor plant's toxicity, which includes alkaloids, glycosides, various resins and volatile oils and is therefore dangerous for crop workers. Some cities and states in the USA are even trying to ban the ornamental use of castor bean plants. As if those concerns aren't bad enough, the plant is also used to produce ricin, a toxic ingredient that is used for chemical and biological weapons. In terms of its use as a biofuel, castor oil is fairly unusual in that it does not need heat to convert into biodiesel, therefore it is less energy intensive.

Key features

- Tough
- High strength
- Low friction
- Good resistance to wear and tear
- Drought resistant
- Easy to grow
- Transparent grades available
- Limited chemical resistance
- Compelling consumer story

Cost

Castor oil commands a higher price than other similar seed oils such as sunflower and canola.

Typical applications

Apart from its common association as a laxative and its other healing properties, castor oil has more than 700 derivatives and uses ranging from lubricants to cosmetics for making soaps, and now, of course, as a source for the plastic industry. As with many polyamides, the main application area of this renewable form is in engineering, or other demanding applications that require enhanced mechanical properties in comparison to commodity plastics.

Sources

Apart from the popular use as an ornament, the castor plant is common in tropical climates such as Brazil and India.

Latex

There are many uses for trees and their fruits that have nothing to do with making products and furniture, or anything to do with the structural part of the plant at all. Cultural history is full of references to liquid remedies, ointments and potions that are derived from trees: for example, the ashes of the beech tree are used for making soap and Maple syrup is refined to create castor oil, which is then used to make Nylon replacements for cellulose such as Tencel® and Rayon®. Latex is the sap of another plant derivative, extracted from the milky juice of several rubber-yielding plants, including the rubber tree.

As with most derivatives of anything that is grown, the properties of latex vary depending on the type of tree it's taken from; the tree's location, age, surrounding climate and the method used for tapping all play a part. Apart from being the raw material for many products, latex is also the commercial base for the production of natural rubber – not to be confused with other synthetic rubbers, which are derived from petrochemicals and are the second major type of rubbers – one of the most versatile and widely used.

Everything about the British footwear brand Terra Plana is considered from an environmental perspective. Manufacturing is geared towards using the smallest number of components possible and very little glue. The organic canvas comes from sustainable sources, synthetic polyamide textiles are made with recycled bottles, and soles are made with reconstituted natural latex and rice husks.

Image: Terra Plana Kariba boot with latex sole

+	–
–Good contact adhesion –Versatile –Strong and resilient –Low-allergen material –Renewable	–Poor chemical and UV resistance

Production
Natural rubber can be formed in lots of different ways. It can be applied to a mould as liquid in dip forming – think of condoms – it can also be cast into solid pieces in a mould, and it can be foamed.

Sustainability issues
As a thermoset material, it cannot be remelted; however, latex and most other forms of rubber are recycled and reused. This is often achieved by grinding down products into crumbs and granules to be used as fillers in other products. Depending on conditions, the rubber tree takes five to 10 years to reach maturity, that is, the stage when tapping can be started. The typical rubber content of the yield from tapping a tree includes anything from 20 to 50% actual rubber.

Typical applications
One of the earliest applications for natural rubber was as pencil erasers. When foamed, it is used for mattresses and cushioning. It is also used as a binder with various fibres to make matting and other cushioning materials. The latex from the Jelutong tree is used in the production of chewing gum. When dip-formed it is used for condoms, balloons and surgical gloves. The glue Copydex is made from latex dissolved in water. The major end-use market for rubber is transportation, by far the largest single sector, with tyres and tyre products alone accounting for more than 50% cent of consumption.

Cost
According to the International Rubber Study Group, the price of natural rubber fluctuates considerably; in 2009 it reached £1,165 ($1,800) per tonne. In 2011 it reached £3,400 ($5,251) per tonne.

Derivatives
Butadiene styrene – the BS in ABS – is a synthetic rubber.

Key features
- Rapidly renewable
- Excellent resilience and tensile strength
- Excellent adhesion (contact adhesives)
- Low chemical and UV resistance
- Antimicrobial
- Unlikely to result in allergic reaction
- Decomposes in landfills

Sources
Natural rubber is obtained almost exclusively from *Hevea brasiliensis*, a tall softwood tree indigenous to tropical and sub-tropical countries. Asia is by far the largest producer of natural rubber, with Malaysia also being a big producer.

OIL BASED

Over the last century, plastics have by far had the most dramatic impact on the world. Defined by their ability to be formed into precise, identical multiples of billions of units they are predominantly made by squeezing hot, sticky liquid into steel cavities. As a material of mass-production, plastic has almost singlehandedly changed the way the world looks by creating products in a vast array of bright colours.

However, the term 'plastic' could be on the verge of becoming as antiquated as Bakelite. Plastics fulfil so many functions that are both practical and essential, such as medical care allowing human organs to be replaced by artificial ones, or the use of plastic in lightweighting for transport, such as the leading edge of the Airbus A380, as well as functions such as the soft, comfort and cushioning under a running shoe or the crystal transparency of a plastic chair.

However, plastic is also tainted with associations of ecological disaster, images of overflowing landfills of disposable plastic waste and poisonous incineration and processing plants, but as we become more familiar with plastic we are finding new versions and new ways of recycling the materials when they are no longer useful. Traditionally plastics are defined as being oil derived, but as the boundaries between families of materials blur and new sources for plastics such as castor oil, featured in the Grown section, are identified, so this definition becomes less precise and less relevant. This section, however, looks at the oil-based plastics that are currently used for design applications and highlights innovations in plastics that allow it to contribute to more sustainable applications. This section is organized into two sub-sections of thermoplastics (plastics that can be re-melted) and thermosets (plastics that cannot be re-melted and are therefore not recyclable).

ABS *(Acrylonitrile Butadiene Styrene)*

ABS is one of the most versatile plastics, and if you are a designer it is an easy choice on a bill of materials and might be the plastic you specify when you can't think of anything else.

It can be rigid, colourful and shiny and its use in Lego shows how it is almost unbreakable for the more than 400,000,000 children who play with Lego every year. As a 'workhorse' of plastic, ABS achieves an extremely high degree of manufacturing tolerance, which is 0.002 mm. This high tolerance is what makes the 'stud-and-tube' principle of a product like Lego work continually, so that the Lego bricks always stick together.

ABS is a part of the styrene family of plastics and is made up from three components or, in technical terms, three monomers; containing about 25 per cent acrylonitrile, 20 per cent rubber-polybutadiene and 55 per cent styrene. The versatility offered by the combination of this blend (A, B and S) comes from the tailoring of the specific properties, and it is the combination of these three ingredients that delivers what is widely recognized as an engineering material with a good balance of properties including toughness, hardness and rigidity. As a result, ABS can provide physical and economic advantages in head-on comparisons with metal, wood and other conventional design materials.

Image: Electrolux Vac from the Sea

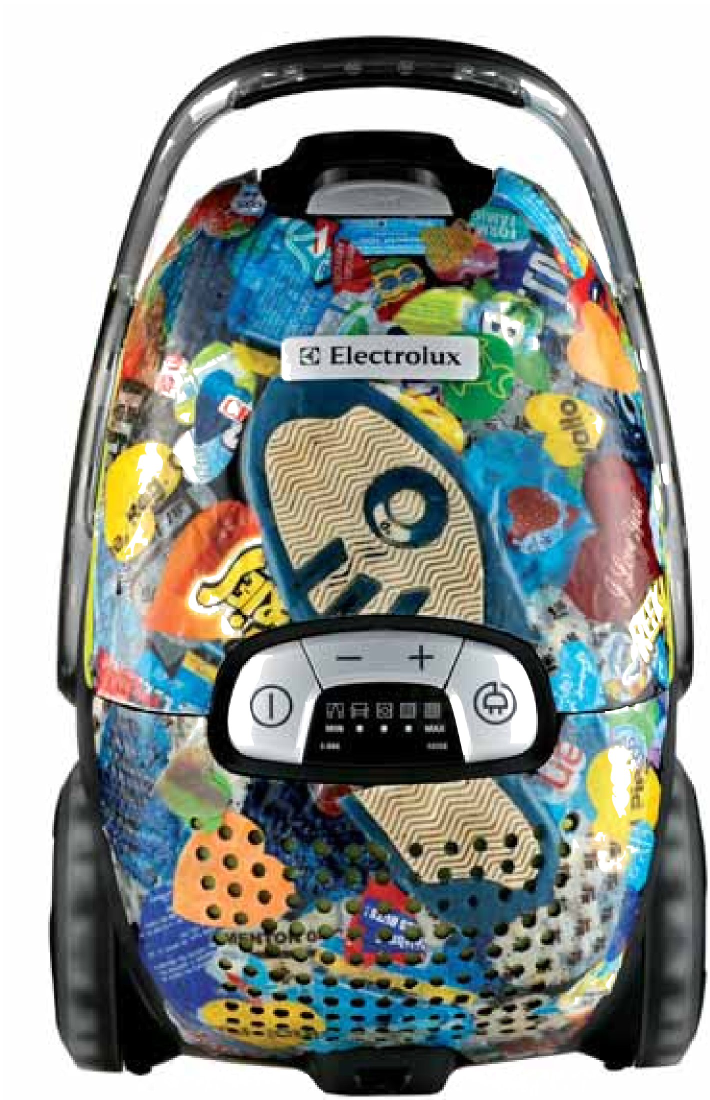
+	–
–Low cost –Versatile –Easy to process –Extremely tough with good impact resistance –Recyclable	–Flammable when exposed to high temperatures –Poor resistance to UV light

Production
ABS can be moulded using all the major plastic processing techniques: injection moulding, extrusion, blow-moulding and structural foam, and can be coated using electroplating processes.
It remains stable during processing, without any major issues such as warping and sinkage – dimples and depressions on the surface of the finished part. It is also very straightforward to exactly match colours.

Sustainability issues
ABS is recyclable, but as it is petroleum-based it is not a sustainable option, although research is ongoing into creating 'green' ABS that uses natural rubber as an ingredient.

Key features
- Versatile processing
- Allows for high tolerance
- Hard and scratch resistant
- Excellent stiffness
- Easy to colour match
- Excellent dimensional stability
- High low-temperature impact strength
- Recyclable

Typical applications
It is impossible to give specific applications for ABS because it is used in so many areas, ranging from Lego, shower trays and food processors to a whole range of other white goods. When blended with PC, it is also used for the housings on mobile phones for extra strength.



Sources
Widely available from multiple global suppliers.

Cost
£1.90 ($3) per kg.

ASA *(Acrylonitrile Styrene Acrylate)*

Plastics are not generally considered to be a group of materials that suffer from degradation; however, as any parent will know, leave a plastic toy outside in the rain, frost or blinding bright sun and you won't have a shiny, brightly coloured piece of plastic anymore. The surface of many plastics age and fade in colour or display something called environmental stress cracking. ASA, however, is a hardier plastic than most with its main distinguishing factor being its ability to withstand outdoor use. It is this resistance to UV rays that separates it from standard moulding materials like ABS. As a result, it is often used in the automotive industry, where parts don't need painting and hold their colour without fading.

The polyacrylates, or acrylics, family, of which ASA is one, occupies a large area of the plastics family as a whole, and is grouped through the general properties of transparency and toughness. ASA and its properties were developed with long-term use in mind, and like ABS, it is a blend of three monomers: acrylonitrile, styrene and acrylate. ASA resins have properties similar to ABS but with a rubber taking the place of the butadiene that exists in ABS. This rubber adds resilience to UV and oxygen degradation, which marks the main distinction and makes it a material suitable for outdoor use. It is this resistance to chemicals and impact, and ability to hold colours that means that ASAs should be a main consideration for external, weather-resistant applications.

Image: Range Rover Evoque with ASA wing mirrors

+	–
–Light resistant –Weather resistant –Widely available –Hardwearing –Easy to colour	- Toxic smoke generation when burned –Concerns over sustainability

Production
As with ABS, this engineering thermoplastic can be easily processed through processes such as injection moulding and extrusion due to its ability to flow well in its molten state, allowing for complex mouldings and large wall thickness ratios. It is a material that is often co-extruded with ABS or PC to enhance the weather resistance of these materials.

Sustainability issues
As with all petroleum-based plastics, there are concerns over sustainability. Thermoplastics can be remoulded, so are therefore recyclable.

Cost
Moderately expensive: £3.80 ($6) per kg.

Sources
Readily available from multiple suppliers.

Derivatives
–Geloy® ASA resin sabic
–Luran®
–Korad®
–KIBILAC®

Key features
- Versatile processing
- Excellent UV resistance
- High clarity
- Good impact strength
- Excellent chemical resistance
- High heat resistance
- Recyclable

Typical applications
This is a material that is able to extend the long service life for products that will live outdoors, and applications can mainly be divided into three main markets: automotive, building/construction and leisure. Specific products include garden furniture, sprinklers, garden lights or extruded glazing and satellite aerials. Other applications include microwave ovens, vacuum cleaners and washing machines.

CA *(Cellulose Acetate)*

Cellulose acetate has to be one of the most seductive plastics. A beautiful surface, uncomplicated processing and it feels warm when you hold it in your hand.

Cellulose nitrate was one of the first plastics to be commercialized when it was first discovered in the mid-nineteenth century, and it later became known as celluloid. Unfortunately, in terms of commercial usefulness it didn't last long because it was highly flammable. Today, cellulose acetate and its cousins from the cellulosics family feature much more often on the designer's radar. It's a material that combines many valid mechanical properties, such as toughness and optical clarity, with a whole list of seductive sensory qualities. Cellulose acetate is made up of two main polymers: cellulose, which is a naturally occurring and abundant polymer derived from treating beech wood pulp, and acetic acid. It can best be visualized by thinking of sunglasses, a product that makes use of the tactile properties of the material.

Alternatives in the cellulosics family include cellulose acetate butyrate (CAB), which has a higher softening point than CA but also has good UV resistance, making it a popular choice for outdoor applications; and cellulose propionate (CAP), which has very similar properties with some grades offering higher strength, making it popular for tool handles. Also, adding a plasticizer to the cellulose propionate mix offers increased impact strength.

Image: Thierry Lasry sunglasses made from Mazzucchelli acetate

+	–
–Tactile so good for 'close to skin' applications –Extremely tough –Widely available	–Poor chemical resistance –Lacks dimensional stability in thin sections

Production
As a thermoplastic material it is suitable for injection moulding, casting or extruding; however, unlike many other thermoplastics, it is not suited to blow-moulding and rotational moulding. If you are considering injection moulding, be aware that it lacks good dimensional stability in thin sections, in which case you may want to consider machining it from a cast block. Due to the availability of the sheet form, it is also suited to both one-off and high-run batch or mass production.

Sustainability issues
The use of wood pulp as part of the make up of CA means that less petroleum is used than for most other plastics.

Key features
- Very tough
- Derived from a renewable source
- Self-polishing
- Feels warm to the skin
- Can be polished by hand
- Poor chemical resistance
- Recyclable

Sources
Widely available; however, much of the raw material comes from Eastman Chemicals and the flat sheet form, which is often used for spectacle frames, comes from an Italian supplier called Mazzucchelli 1849.

Derivatives
Mazzucchelli is an Italian supplier of a range of cloudy, swirly patterned CA sheet, which is largely used as the basis for frames for sunglasses. M49 is one of their products, which is 100%

Typical applications
Because of its many warm, friendly properties it is used in all sorts of 'close to the skin' applications, including toothbrushes, tool handles, hair clips, cutlery handles, toys, playing cards, dice, screwdriver handles and spectacle frames for sunglasses. It is also extensively used in other fashion accessories like bag clasps and fasteners, belts and jewellery.

Cost
£2–3 ($3-5) per kg.

EVA *(Ethylene Vinyl Acetate)*

It's interesting to consider how a material has been used in certain applications because it gives you a route to understanding a lot about its properties. For example, EVA is used a lot in running shoes because it has good cushioning properties and because the shoes need to withstand a massive amount of wear and tear. If you consider that quite often we run in cold weather, then it follows that EVA is also good at withstanding cold temperatures – while remaining flexible. Lastly, it's also a product that's going to be run through some chemicals now and again, like oil and grease and therefore must be fairly resistant to a wide range of chemicals.

EVA is possibly one of the most common types of materials used in running shoes. It's a versatile, soft, rubbery copolyester that is adaptable in how it can be processed, from dense rubbers to the aerated forms that give the cushioning in running shoes.

Although there are clear grades, EVA in its natural state has a pale translucency that means it accepts colour very easily. It is softer, clearer and more rubbery than LDPE, making it less likely to crack, but varying the levels of vinyl acetate, which can be between 4 per cent and 30 per cent, can alter the transparency and also the flexibility. Adding more increases the transparency and flexibility. For other rubbery materials consider silicone for greater temperature resistance, and TPEs or TPVs.

Image: Croc sandals

+	–
–Tough and shock absorbent –Soft and flexible –Takes colour well –Widely available –Recyclable	–Not as resistant to very high temperatures as it is to cold

Production
As with many thermoplastics, EVA can be injection moulded, extruded, blow moulded and thermoformed. Parts can also be welded using a variety of methods, including ultrasonic, hot plate and radio frequency. EVA is also good at absorbing fillers. In packaging applications EVA can be processed into extruded, blown or cast films and easily blended with other materials.

Sustainability issues
Low melt temperature means that it is not energy intensive. EVA is recyclable.

Typical applications
One of the most ordinary applications is as the glue in hot glue guns, which exploits its low temperature resistance. However, EVAs are used in a wide range of products, including the soles of running shoes, car mats, handle grips, some staplers have EVA base pads, flexible tubing, bicycle saddles, old vinyl record turntable mats, vacuum cleaner hosing, as a replacement for PVC in medical devices, protective bumpers, ice cube trays and in the ultimate multipurpose lounging shoe, Crocs. It is often used as an alternative to PVC, and because of the lack of plasticizers to increase flexibility, is suitable for things like baby teats.

Cost
Low cost: £1.50 ($2.35) per kg

Key features
- Excellent energy absorption
- Excellent toughness
- Good flexibility and softness
- Low melting temperature 65˚C (149ºF)
- Easy to colour
- Biologically inert
- Recyclable

Sources
Widely available from multiple global suppliers.

Ionomer Resins

The less common families of engineering polymers, like ionomer resins, tend not to register at the forefront of designers' minds, probably because they have performance characteristics that are best suited to very specific product requirements. But what's important to me as a designer is that, although it would be simpler if you could categorize the properties of materials based on their product applications, there are some plastics that have applications and formulations that are so diverse it is difficult to characterize them in a straightforward way. Ionomers falls into this category, with Surlyn®, one of the big engineering polymer brands from Dupont, being one of the most recognized ionomer brands.

Essentially, this polymer can be summarized as having outstanding impact strength, even at low temperatures; scuff, abrasion and chemical resistance, with extremely high optical clarity, which, combined with its mouldablilty, means it can be more versatile than glass for transparent products.

However this material, which has numerous high-performance and 'special' characteristics, can be marketed in a way that gets designers to find new applications for its many properties. Ionomers appear in many varied forms, they are used for their crystal clear clarity in the injection-moulded walls of perfume bottles, for squeezable, soft extruded shampoo tubes, and even in the tough, resilient material of a dog chew.

Image: Golf balls

+	–
–Extremely tough and resilient –Good chemical resistance –Versatile –Widely available –Recyclable	–Petroleum-based so not the most sustainable option

Production
Ionomers can be injection moulded, extruded, foamed, thermoformed or used as a powder-coating or resin modifier to give extra strength to other polymers. They also offer direct adhesion to metal, glass and natural fibres through heat lamination.

Typical applications
Because of their strong impact resistance, ionomers lend themselves to a range of abusive environments, such as the end of a tool handle that gets hit with a hammer or in the ten-pin bowling lane for the pins. It is also used as a material for dog chews, an equally gruelling and robust application. One of my favourite applications is in golf balls. Apart from these extreme cases, ionomers do have a softer side and, with their excellent chemical resistance and clarity, they make ideal glass and crystal replacements for perfume bottles. In film form, ionomers are used in a range of food packaging including fresh meat and fish, which exploit its toughness. Other applications include hockey helmets, footwear, body boards, tool handles, glass coating, ski boots, automotive fascias, perfume caps and bath and kitchen door handles.

Sources
Widely available from multiple suppliers.

Sustainability issues
Petroleum-based, so not sustainable long term, but can be recycled. Also being used to make lighter packaging materials.

Cost
£2 ($3) per kg.

Key features
- Outstanding impact toughness
- Abrasion resistant
- Scuff resistance
- Good chemical resistance
- High clarity
- High melt strength
- Recyclable

Liquid Crystal Polymers *(aka Liquid Crystals)*

The sports industry has a thirst for new materials and technologies, using them just as much to create heroes for a specific brand story as they do to enhance performance. In the Nike Flywire® technology used in the Lunar Racer shoe, a new material sandwich was designed to create this ultra-lightweight running shoe. The material hero in these shoes is Vectran® a brand of fibres that is a quarter of the diameter of a human hair and weight-for-weight, five times stronger than steel. These fibres are sandwiched between a TPU (thermoplastic polyurethane) mesh to create a shoe upper that is as thin and translucent as a second skin. Vectran® is classified as a liquid crystal polymer (LCP).

It's difficult to describe succinctly the technical background regarding LCPs, partly because they are neither solid nor liquid. The dual properties of fluidity and solidity are partly due to the crystal structure that makes up the solid. In this state the crystals have different properties along different axes, a characteristic known as anisotropy. These two properties deliver vastly different types of materials. For instance, they are used in TVs in their liquid form and in their solid form take the form of super fibres such as Vectran® or Kevlar®, both of which are known for extreme tensile strength. Vectran® is a fairly new addition to the LCP family of fibres and appears to have a successful product application in the Nike shoe.

Image: Nike Lunar running shoe

+	–
–Extremely strong and lightweight –Good chemical resistance –Easily moulded –Recyclable	–Forms weak weld lines –Relatively high cost –Only available from specialist suppliers

Production
LCPs can be formed using conventional thermoplastic techniques and are suited to thin, sectioned, intricate shapes. This is due to the fact that when injection moulding LCPs they display excellent flow which means they can be moulded into very thin sections.

Key features (solid LCPs)
- Good chemical resistance
- Extremely high strength
- Excellent abrasion resistance
- Excellent dimensional stability
- Retains properties at high temperatures
- Excellent cut resistance
- Food grade
- Brittle in one direction
- Recyclable

Sources
Available from specialist suppliers.

Cost
Relatively high cost of raw material is offset by lower manufacturing costs.

Sustainability issues
Petroleum-based, so not sustainable long term, but can be recycled.

Typical applications
Apart from fibres, one of the major applications is in LCD displays, where the liquid crystals are sandwiched between two pieces of glass, with a voltage changing the arrangement of the crystals. Another design friendly application is in switchable frosting window glass, which works on a similar principle to the TVs. Forms of solid LCPs have also been used to replace stainless steel in medical applications due to their high temperature resistance meaning the products can be sterilized. Another area in which liquid crystals are used is in thermochromic effects, surfaces that change colour according to temperature.

Derivatives
–Xydar®
–Vectra®

Melamine Formaldehyde *(aka Melamine)*

Melamine occupies a unique place in the plastics family. Having been used since the 1930s it is one of the oldest commercially used plastics and still has no major replacement in relation to its use in plastic tableware. Just think of its bright colours, the hard, clanking sounds as bowls knock together and the stiffness and hardness that resembles ceramic. No other thermoplastic comes close to offering this same combination of characteristics.

Melamine is from the same thermoset family as urea and phenol formaldehyde. It offers an excellent surface finish with a much better ability to take colour, but it is generally more expensive. It imparts absolutely no smell or taste to food and feels hard, dense, rigid and unbreakable. The hard, shiny nonporous surface is part of the reason that it has long been a popular alternative to ceramics in the design of dishes, plates and bowls.

In the 1930s melamine compounds were an early replacement for Bakelite due to their ability to absorb and retain a range of colours. The 1950s were the heyday for moulded melamine when they were widely used for bright, multicoloured tableware products.

Image: Hands On™ salad bowl by Joseph and Joseph

+	–
–Good resistance to chemicals, impact and heat –Non-toxic –Excellent surface finish –Takes colour well	–Relatively expensive –Cannot be recycled

Production
Melamine is available as a compound and a resin and so can be injection moulded, compression moulded and extruded. Unlike many thermoplastics it can be moulded with variable wall thickness.

Sustainability issues
As with all thermosets, melamine cannot be remelted and remoulded.

Key features
- Excellent chemical resistance
- Excellent electrical insulation
- Easily coloured
- Excellent hardness
- Excellent stiffness
- High impact strength
- Food grade
- Easy to colour match
- Excellent dimensional stability
- Not recyclable

Typical applications
Its heat resistance makes it the perfect material for ashtrays, handles for cooking pots, fan housings, circuit breakers, coat buttons, dinnerware and plastic laminates. Its excellent hardness and chemical resistance make it scratch resistance and stain free, ideal for kitchen worktops and moulded kitchen utensils.

Cost
Compared to other thermosets it is expensive: £1.20 ($1.90) per kg.

Sources
Widely available from multiple global suppliers.

PA *(Polyamide)*

When it was discovered, apparently by accident, in a DuPont laboratory, polyamide provided 1940s culture with a revolutionary material. Nylon, which is DuPont's trade name for polyamide, established itself as part of popular culture, where its original potential was seen to be as a replacement for silk, and became a poster boy for the coming plastics age. It goes without saying that one of its major properties is its slippery silkiness, toughness and tensile strength, which is why it was such an innovation in women's stockings.

Polyamides fill pretty much every aspect of our daily lives, from the bristles in a toothbrush to the sole of a shoe. As a moulded material, over the years polyamide has muscled in on applications where metals have previously been used. There are many, many formulations of polyamide: PA 6,6; PA 6,12; PA 4,6; PA 6; and PA 12 are some of these with multiple grades in-between. The two most popular grades are PA 6,6, (the most widely used) and PA 6. Generally, the mechanical properties of these grades are similar; however, the lower the number, the lower the melting point and generally the lighter the weight. Although characterized by its strength, stiffness and toughness, polyamide's main drawback is its poor moisture resistance, which reduces its strength and means that parts, particularly those with thin wall sections, are particularly dimensionally stable.

Image: Rainbow trivet by Normann Copenhagen

+	–
–Widely available –Resistant to high temperatures –High tensile strength –Low friction –Recyclable	–Limited chemical resistance –Poor moisture resistance

Production
It is difficult to extrude due to its low viscosity but is well suited to standard injection moulding. It can be spun into fibres, extruded for multilayer films for bottles and is capable of being filled with materials including glass fibres to enhance its properties. Plasticizers can be used to increase flexibility.

Sustainability issues
As a thermoplastic, it can be recycled; post-consumer PA is currently not recycled in large quantities but recycled post-industrial PA is provided by some suppliers. Fibre-reinforced grades are difficult to recycle.

Sources
Widely available from multiple global suppliers.

Key features

- Low friction
- Excellent resistance to abrasion
- High strength
- High temperature resistance
- Blends well with other materials
- Poor moisture resistance
- Limited chemical resistance
- Recyclable

Derivatives

–Nylon®
–Perlon®
–Nexylon®
–Grilon®
–Hahl PA®
–Monosuisse PA®
–Enkalon®
–Stanylenka®

Cost

PA 6 is £2.55 ($4) per kg.

Typical applications

Fibreglass-reinforced grades can replace metal in many cases, including structural parts in furniture and hardwearing applications such as sports equipment. It's also found in fabrics, carpets, strings for musical instruments, seat belts, gear bearings and cams. Nylon fibres are used in textiles, such as fishing lines and carpets. Nylon film is used for food packaging, offering toughness and low gas permeability, and because of its good temperature resistance, it's used for boil-in-the-bag food packaging.

PBT *(Polybutylene Terephthalate)*

As products become miniaturized and the demand on materials to perform at increasingly thin sections becomes greater, plastic suppliers are looking to create materials to facilitate this trend, while still giving the torsional strength that consumers have come to expect from high quality products.

Polybutylene terephthalate (PBT) is a tough engineering polyester belonging to the same family as PET. Its main performance characteristic is its high strength and stiffness. Another major benefit is its versatility due to the grades in which it is available and also the range of fillers and reinforcements that it can be moulded with. As a stiff material, PBT has none of the flimsiness associated with some of the commodity plastics such as PP, PS and HDPE. Instead, providing even greater strength than engineering materials like ABS, PBT offers users a feeling of high value, sturdy components even in small thin-walled mouldings.

As a polyester, PBT crystallizes rapidly, which means that when moulding components for products, the cycle times are relatively short and moulding temperatures can be lower compared to many other high-performance plastics. It is also a good candidate for adding reinforcing materials to, such as glass fibre, to increase tensile strength. Another one of its assets is its chemical resistance, which is the main reason it is often blended with PC.

Image: Myto chair by Konstantin Grcic

+	–
–Strong and tough –Hardwearing –Short production times –Widely available –Recyclable	–Relatively expensive compared to standard commodity plastics

Production
PBT moulds at lower temperatures than other plastics, leading to short production cycle times in injection moulding. PBT can also be extruded and blow-moulded, it can also be used as an encapsulation material. In electrical applications and PBT, components can be laser welded together. It is extremely good at accepting surface finishes and plating and film sublimation for highly durable decoration. PBT also accepts fillers and reinforcement such as mineral and glass fibres for increased stiffness.

Sustainability issues
Excellent flow properties mean that PBT is less sticky in the mould and requires less heat when moulding, leading to a less energy intensive process and faster cycle times.

Derivatives
–Ultradur®
–Crastin®

Cost
£3.20 ($5) per kg.

Key features
• High strength
• Excellent stiffness
• Outstanding impact toughness
• Excellent wear resistance
• Good resistance to chemicals
• Long-term use at high temperature
• Accepts fillers and reinforcement
• Recyclable

Typical applications
Applications include exterior trim applications for cars, for example windshield wiper covers, handles and mirror housings. Consumer electrical uses include oven door handles and iron handles. It is also the material from which South Korean designer Min-Kyu Choi designed his award-winning folding electrical plug.

Sources
Widely available from multiple global suppliers.

PC *(Polycarbonate)*

There are many materials with high transparency, but combine this quality with toughness, and the most widely available and suitable plastic is polycarbonate. Polycarbonate is popular as the plastic alternative to glass in applications as varied as glazing and drinking vessels. The drinks industry has, for some time, looked to PC as the material to replace traditional glassware for various public drinking venues, where crimes committed with broken glass are an increasing safety problem. It is one of the toughest thermoplastics and this toughness is combined with excellent clarity and to some degree scratch resistance. Although anybody who has ever put one of these glasses in a dishwasher will tell you that it won't take long for the haziness of a well-used glass to appear. One of the advantages of PC is that it is easily blended with other plastics, such as ABS or PET, to enhance the toughness of these additional materials.

Increasingly, PC has become associated with BPA, a synthetic oestrogen and potential hormone disruptor, which is used as an ingredient to enhance its hardness. BPA can leach from the material during usage and normal wear and tear when the plastic is scratched or stressed. Ultimately, this may result in it being withdrawn from food contact products such as babies' milk bottles.

Image: Front Page magazine rack by Kartell

+	–
–Highly versatile –Easy to work –Tough and resistant –Excellent clarity –Widely available –Recyclable	–Energy intensive to process –Possible problems with biocompatibility

Production
Various grades are available, but as a standard material it is used for high-volume, mass-production via injection moulding, extrusion, blow-moulding and even foaming. All of these processes are widely available in standard machines. It is also a material that is available in extruded sheet form, where it is often used for glazing. These are not just flat sheets but also structural ribbed sheets.

Sustainability issues
As with all thermoplastics PC can, if not mixed with fibres, be re-melted and reused (its identified by the recycling symbol number 7). One of the key features of polycarbonate is its ability to withstand high operating temperatures; however, the downside of this is that it requires a lot of heat energy to process it.

Sources
Widely available from multiple global suppliers.

Derivatives
Lexan®

Key features
- Versatile processing
- Very tough
- Excellent clarity
- Reasonable hardness
- High operating temperature
- Recyclable

Typical applications
It is blended with ABS to add impact resistance for mobile phone casings; its clarity makes it suitable for shatter-resistant windows; its toughness is suited to visors on crash helmets and eyeware. It is also the material of the CD and DVD and was used in the casing in the iconic first generation iMac.

Cost
£2.90 ($4.50) per kg.

PEEK *(Polyetheretherketone)*

Materials and applications are in a state of constant movement: metals replacing plastic, plastics replacing wood, ceramics replacing plastics, etc. Materials 'bandits' are hijacking properties that are more commonly found in other materials families and using them in products.

At the top of the polymers family tree, with properties beyond conventional engineering polymers, exists the group of ultra polymers. This group encompasses materials that are fairly uncommon in design, such as sulphones, polyamide-imides and polyetheretherketones (more commonly known as PEEK). These plastics, which have properties that go beyond most physical and mechanical characteristics of plastics, occupy a top tier of performance engineering, with features that allow them to infiltrate applications that traditionally belong to other materials such as metals.

There aren't many applications where you would actually see this material and admire its properties. Regarded as a high performance polymer, PEEK has a long list of properties that make it suitable for a range of demanding, high-end engineering applications. These properties are characterized by high stiffness and chemical resistance that, unlike for most other plastics, are maintained at high temperatures. As a result of these properties, PEEK demonstrates its superior nature by being used to replace aluminium and other metals in various industries.

Image: Carbon nanotube enhanced PEEK, Solvay plastics

+	–
–Easy to process –Robust and hardwearing –Biocompatible –Widely available –Radiation resistant –Recyclable	–High cost limits its application to high performance engineering components

Production
Although there are other plastics with high-performance traits, the benefit of PEEK is that it can be formed using conventional moulding machinery. It offers advantages over conventional low-temperature metals such as zinc and aluminium or magnesium die-casting, which have higher material costs and shorter mould lifespans. Recent introductions by Victrex, a leading manufacturer of PEEK, are PEEK coatings and PEEK film. In film form, the material (available in thicknesses ranging from 6-750 microns) is used in anything from speaker diaphragms to microphone spacer film for mobile phones, which need to withstand high temperatures during the manufacturing process. As a coating it is applied to a range of metal substrates to increase chemical resistance.

Sustainability issues
PEEK is one of the purest and most stable polymers, so does not contain additives that might be released during heating in the moulding process. This also makes it suitable for implantation in the body in the medical industry.

Typical applications
Its high cost means that applications tend to be limited to engineering components, which require high performance structural and mechanical properties: typical examples are bearings, bushings, coatings, protective tubing and electrical connectors. It is also used in the medical industry because it can be continually sterilized and is biocompatible. A new application being explored is using PEEK as a metal replacement for gears in automotive gearboxes as a way to reduce engine noise. As a film it is also used for acoustic insulation in aircraft interiors. In the food industry it is used in aseptic packaging, which needs to have operating temperatures high enough to kill bacteria. However, for a more visible consumer application, PEEK has been used as the inner pot for rice cookers, which had traditionally been made from aluminium and were susceptible to corrosion.

Derivatives
PEEK is also available in glass or carbon-filled grades and Swiss-based Sefar have produced PEEK-based fabrics.

Cost
High cost: £64 ($100) per kg.

Sources
Widely available from multiple global suppliers.

Key features
- Versatile processing
- Retains its properties up to 300ºC (572ºF)
- Excellent wear and fatigue resistance
- Excellent chemical resistance
- Radiation resistant
- Recyclable

PF *(Phenol-formaldehyde, aka Phenolic)*

Phenol-formaldehyde conjures up feelings of 'olden times', its brown semi-gloss reminds me of junk sales where tatty second-hand products wait for a time when fashion makes them desirable once again. Not something that is likely to happen with this plastic of a bygone age.

Developed by LH Baekeland in 1907, phenol-formaldehyde was a pioneering thermoset plastic that heralded the plastic age that was to define the twentieth century. Today, formaldehyde plastics have limited applications due to the greater range of processes that can be used on thermoplastic materials.

At first, the visual language of phenol-formaldehyde borrowed from other materials, attempting to replicate wood or ceramic products in its murky brown surface. It was not until the mid-twentieth century that newer plastics were developed, which were more readily manufactured in bright colours as opposed to the dark palette of Bakelite.

Like many early plastics, Bakelite benefited your social status. In terms of applications it can be compared with urea, melamine formaldehyde and urea formaldehyde, but with less of the availability of colour that melamine offers.

Image: Le Creuset pan handle

Production
As a thermoset plastic it has limited processing potential. However, it can be compression moulded and is available as cast resins, which could be machined or carved into shapes. Unlike most thermoplastics it can be moulded with variable wall thickness.

Sustainability issues
As with all thermosets, phenol-formaldehyde cannot be re-melted and re-moulded.

Sources
Available from multiple global suppliers.

+	–
–Low cost	–Limited colour Sources
–Sturdy and resistant	–Can be brittle
–Excellent dimensional stability	–Not recyclable
–Widely available	
–Non toxic	

Derivatives
–Bakelite®
–Novotex®
–Oasis®

Key features
• Excellent chemical resistance
• Excellent electrical insulation
• Limited in colour availability
• Excellent heat resistance
• Excellent hardness
• High impact resistance
• Excellent dimensional stability
• Brittle if moulded in thin walls
• Not recyclable

Typical applications
Today, the use of phenol-formaldehyde for consumer goods is limited to a few applications. These include oasis foam for flower arranging, binding for laminated wood panels, ashtrays, perfume bottle caps, bowling bowls, saucepan handles, door handles, domestic plugs and switches and steam iron skirts.

Cost
£1.30 ($2) per kg.

PCL *(Polycaprolactones)*

Polycaprolactones are a range of thermoforming plastics that have some wonderfully surprising characteristics. In a sense, their range of properties contrast with many of the traditional preconceptions about plastics: first, that most plastics require high heat and pressure to form; that they require expensive steel tooling to shape; that they are not biodegradable; and that they are not compatible with use inside the body. Polycaprolactones, however, are a group of plastics that are more of a sensorial and indulgent material, a characteristic that is primarily based on its melting temperature, which is much lower than for other plastics. This quality gives polycaprolactones a personality closer to a lump of children's plasticine than a material of mass-production.

It is this low melting temperature that is its most noteworthy feature. Melting at between 58–60°C (140°F) means that polycaprolactones melt in a cup of hot water from a kettle, forming a soft, gum-like plastic that can easily be pulled, stretched and shaped. When it cools and returns to room temperature it can be machined, drilled and cut until it is put back into hot water when it can be re-melted. As a result it's a plastic that has found a home in both the classroom and in the factory. This material takes plastic to a completely new venue; a place where it can be formed by hand in a manner that is closer to cooking than anything else in the world of mass-production.

Image: Amateur Masters Chairs by Jerszy Seymour

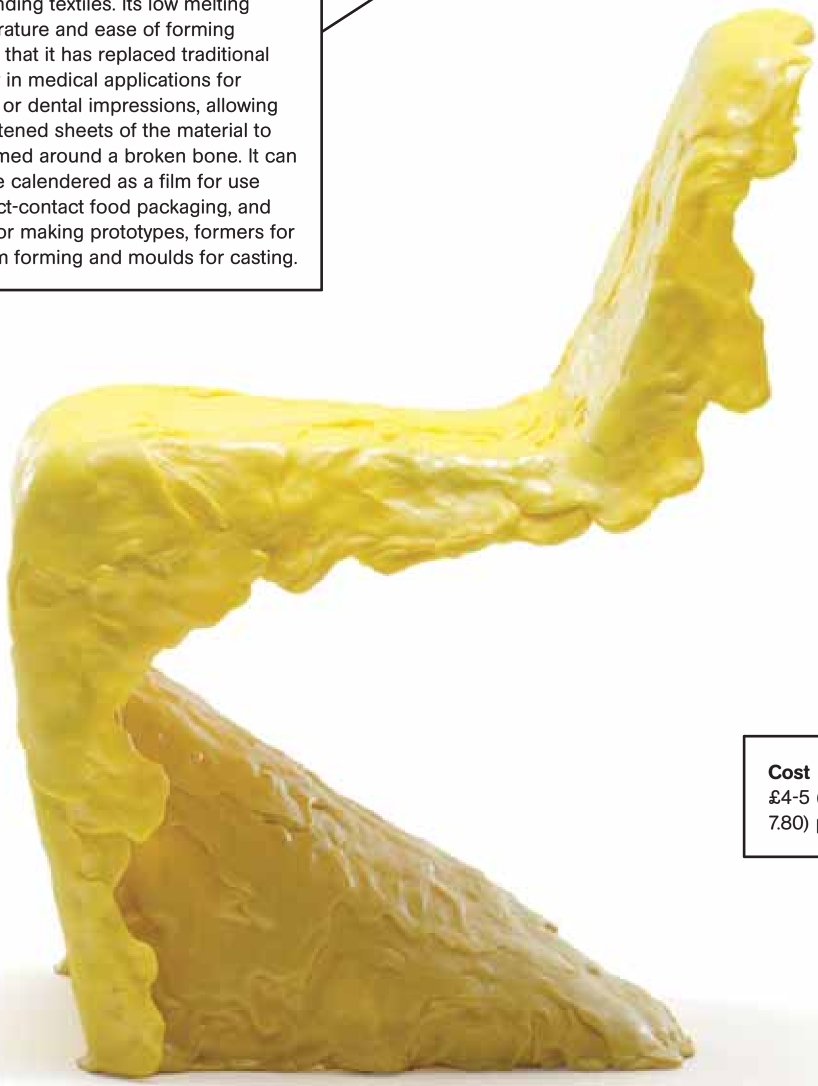
+	–
–Very easy to form at low temperatures –Biodegradable –Excellent strength and resistance –Recyclable	–Derived from crude oil, so not from a renewable resource

Production
Polycaprolactones take the form of granules or powders and can be processed using standard thermoplastic methods: injection moulding, extrusion and calendering to produce films. It can also be used as an adhesive. Its most notable characteristic is its low melting temperature, which allows it to be formed by hand once the granules have been melted in boiling water. This quality allows for thick and solid wall sections to be made, something that is generally hard to do in injection moulding. It can also be machined with standard cutting tools once it has hardened at room temperature.

Sustainability issues
There are two advantages to this plastic in relation to the environment. The first is the low melting temperature, which means it is less energy intensive when processing, and secondly, it is biodegradable.

Typical applications
Polycaprolactones have been combined with PET in seatbelt fibres to enhance cushioning and flexibility, they have also been successfully used for making garbage bags in Korea, and as an adhesive it has been used in shoe sole bonding, laminated packaging and for bonding textiles. Its low melting temperature and ease of forming means that it has replaced traditional plaster in medical applications for splints or dental impressions, allowing for softened sheets of the material to be formed around a broken bone. It can also be calendered as a film for use in direct-contact food packaging, and used for making prototypes, formers for vacuum forming and moulds for casting.

Derivatives
–InstaMorph®
–ShapeLock®
–PolyMorph®
–Plastimake®
–Protoplast®



Cost
£4-5 ($6.20-7.80) per kg.

Key features
- Forms at low temperatures
- Non-toxic
- Biodegradable
- Easily adheres to other materials
- Excellent strength
- Good abrasion resistance
- Good UV resistance
- Recyclable

Sources
Widely available.

POM *(Polyoxymethylene)*

The first thing to understand here is that there is a much simpler, shorter description for polyoxymethylenes: acetals. The second thing is that, unlike other plastics that end in 'ene', for example polystyrene, polyethylene and polypropylene, acetals are engineering polymers, which means that they are a material with superior characteristics, particularly in the areas of strength and toughness, to the point where they are seen as an alternative to Nylon. Nylon is often used as an alternative to metals, so you get the point.

This strength and toughness means that one of the applications of acetals that you are likely to encounter on a daily basis is their use as clips, the kind that you find on all sorts of bags and rucksack straps that click together. This springy quality is what allows them, to a certain extent, to replace metal for tough applications. This springiness is also what makes this material suited for use as guitar plectrums. To get a sense of how it feels, you could think of another widely used application, which is opaque plastic pocket lights, with their slightly oily surface.

Image: Guitar plectrums by Dunlop

+	−
–Widely available –Low friction –Strong and flexible –Recyclable	–Only available in opaque grades –Requires an additive if the product is to be exposed to UV

Production
Standard thermoplastic techniques.

Sustainability issues
As a thermoplastic, POM is recyclable but the material is currently not being recycled in any large quantities.

Key features
- Self-lubricating
- Waxy surface
- Excellent flex strength
- Excellent chemical stiffness
- Poor UV-inhibitor
- Poor clarity
- Recyclable

Cost
£2.35 ($3.70) per kg.

Derivatives
–Ultraform®
–Delrin®
–Celcon®
–Hostaform®

Sources
Widely available from multiple global suppliers.

Typical applications
POM's low-friction properties make the material a good choice for applications with moving parts, such as bearings, wheels and other mechanical components. The material is often used for its ability to flex and spring back again and again, which makes POM a suitable candidate to replace metals in many applications. Needs UV-inhibitor additive for applications that are exposed to daylight.

PPSU *(Polyphenylsulphone)*

Designers are generally familiar with the classification of plastics under the common name thermoplastics, meaning plastics that can be melted and re-moulded, and thermoset, meaning materials which cannot be re-melted; however, it pays to understand the hierarchical structure of commodity, engineering, high performance and ultra polymers. The higher up a plastic is in this pyramid, the more specialized and sophisticated the properties. At the bottom you will find the most standard plastics and at the top is polyphenylsulphone, a high performance plastic for very specific applications.

As in so many instances, plastics are taking the place of metals. For example, the medical industry requires materials and products that are strong, can withstand sterilization, and be moulded into intricate shapes: stainless steel has been the traditional material of choice as it is corrosion resistant and hard wearing, qualities that have remained unsurpassed by other materials for a long time. However, they are limited as it is not easy to make them into complex shapes. Step in polyphenylsulphone, plastics and thermoplastics that are characterized by their transparency, rigidity and stability at high temperatures. This range of materials is designed for harsh environments, where they can withstand temperatures of up to 207°C (405°F). In their natural form they are stable and self-extinguishable, where other materials need modifiers to offer this.

Image: Surgical tray, MacPherson Medical

+	–
–Easy to process –Strong and rigid –Resistant to very high temperatures –Resistant to chemicals –Recyclable	–High cost limits use to specialist applications –Poor UV-resistance

Production
PPSU resins can be formed using standard plastic moulding techniques. It is also available in sheets, which can be thermoformed.

Sustainability issues
Recyclable.

Cost
High cost, though Solvay, the makers of Radel®, offer Acudel® (a modified PPSU) as a more cost effective option for less demanding applications.

Sources
Readily available from multiple suppliers.

Key features
- High temperature resistance
- Good chemical resistance
- High impact strength
- Good transparency
- Rigid
- Biologically inert
- Low toxic gas emissions
- Easily processed
- Food grade

Typical applications
As has already been mentioned, a high number of applications are in the medical industry, items such as instrument trays and surgical equipment handles and components, which need to be continually sterilized and also to withstand being thrown around. However, PPSUs are also used extensively in the aircraft industry for seats, where they provide low heat release and low smoke and toxic gas emissions.

Derivatives
–Radel®
–Quadrant®
–Ultrason® P

PS *(Polystyrene)*

Despite its crystal-like clarity, polystyrene isn't a material that suggests quality. Think of the rustling sound of the tray in a box of chocolates or an Airfix model kit – it is a plastic that has entered our consciousness in the same way that PVC and polythene have. As with polythene and polypropylene, it is a material that, from a designer's perspective, is inexpensive and easy to process.

One of its major features is its water-like clarity; just think of the little compartments that you have in your fridge or the iconic BIC pens. It is also pretty hard and accepts colour well, and if you think about how thin the sections of a cheap disposable plastic cup are, you get an idea of its rigidity. Although it doesn't have as many variations as polythene, polystyrene has a variety of different grades. HIPS or high-impact polystyrene, for example, is the result of rubber particles being added to improve impact strength.

Also included in the family of styrenes are compounds such as ABS, SAN and SMA, which offer enhanced properties that make them suitable for engineering applications. Also in this family is expanded polystyrene, a plastic with a completely different visual identity to standard polystyrene and which forms the kind of packing foam you find when you take your new TV out of its box.

One of the most interesting reuses of standard polystyrene cups is by Remarkable Pencils, who collect and recycle the thousands of cups discarded at water coolers into new, brightly coloured pencils.

Image: Sparkling chair, Marcel Wanders for Magis

+	–
–Easily moulded –Excellent clarity –Good stiffness and strength –Widely available –Recyclable	–Can be quite brittle in its pure form

Production
As a commodity plastic it can be widely processed through all the standard techniques including injection moulding, thermoforming, foaming etc. In its pure form it is quite brittle, blending it increases strength but reduces optical clarity.

Sustainability issues
As the company Remarkable demonstrate through the number of up-cycled products they produce, PS is one of the most recycled plastics. It is identified by the number 6 in the recycling symbol.

Typical applications
Due to its low-cost and ease of processing it has a large number of uses, such as disposable cutlery, cups, plates and food packaging. Other areas include CD cases; BIC pens and razors, fridge compartments, Airfix model kits, which take advantage of its brittleness, and of course, chocolate box trays. Expanded polystyrene is used as a packing material and thermal insulation.

Cost
£1.30 ($2) per kg. PS is one of the cheapest transparent plastics.

Derivatives
Members of the family, with their abbreviations:
–HIPS (high-impact polystyrene)
–EPS (expanded polystyrene)
–ABS (acrylonitrile butadiene styrene)
–SAN (styrene acrylonitrile)
–SMA (styrene maleic anhydride)

Key features
- Versatile processing
- Naturally brittle
- Excellent clarity
- Good stiffness
- Low shrinkage rate
- Recyclable

Sources
Widely available from multiple global suppliers.

PTFE *(Polytetrafluoroethyl, aka Fluoroplastics)*

Discovered in the 1930s by accident – which is the case with so many plastics – PTFE has become one of the most high-profile plastics in history. One of the easiest ways to remember PTFEs is to think of Teflon® from DuPont, a word that has become synonymous with non-stick, and a material that has become a household name and a part of common vocabulary. On that basis, it's not hard to guess that its main property is that it is self-lubricating and super slippery and extremely good at resisting chemicals even at high temperatures.

Having said that, its main drawback is that, unlike most of the other materials featured in this book, it is extremely difficult to process by conventional plastic forming techniques. However, this has not stopped it from becoming widely used as a coating in all sorts of applications, including fabrics such a Gore-Tex® and as a major ingredient of the tent structure of the Millennium Dome.

To create solid shapes a processing method called ram extrusion is used, which allows the manufacture of tubes, rods and sections. PTFE powder is fed into an extrusion pipe, compressed by a ram and transported through the pipe, which is heated up to sintering temperature, so that it sinters together into a continuous extrudate.

Image: Dental floss

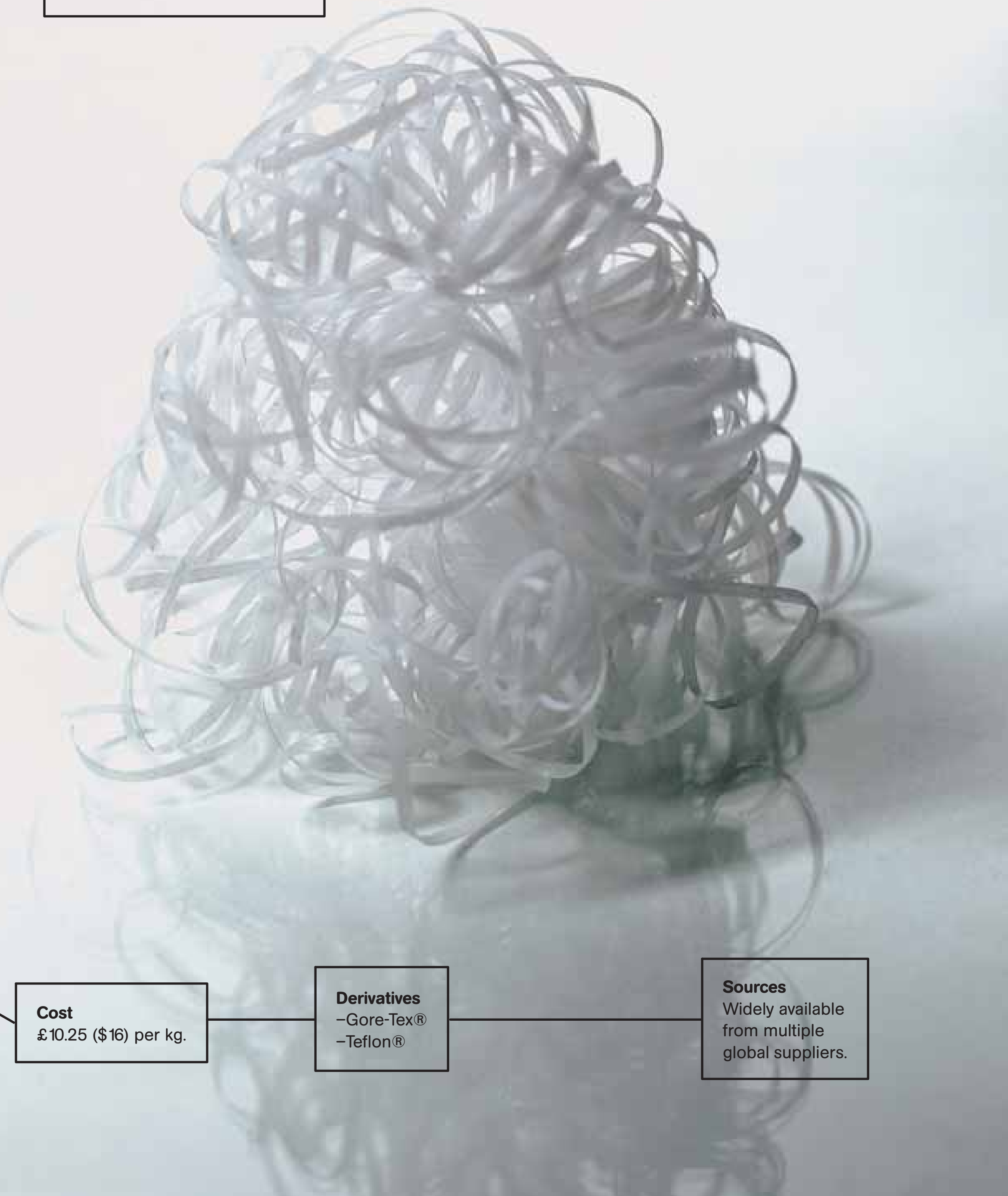
+	–
–Excellent heat resistance –Non-stick properties –Widely available	–Difficult to process into solid shapes –Some PTFEs have been found to use carcinogens during processing

Production
Unlike many other plastics, PTFEs cannot be injection moulded due to the high viscosity of the resin; as a result, solid shapes are difficult to form. However, it can be compression moulded from powder and ram extruded, although its main area of application is being sprayed as a thin layer.

Sustainability issues
Recently there have been a number of claims and law suits on the basis that a key processing agent, perfluorooctanoic acid (PFOA), used in some PTFEs is a potential carcinogen and has been found in the environment and marine organisms.

Typical applications
Apart from the popular name of Teflon®, where it is applied to fabrics and cookware, it is also applied as a coating and lining for chemical equipment, tubes, films, sheets and tape, as a coating for the underside of irons, and infused in ski wax.

Key features
- Excellent heat resistance
- Non-stick
- Excellent chemical resistance
- Excellent UV resistance
- Non-flammable
- Difficult to form
- Food grade



Cost
£10.25 ($16) per kg.

Derivatives
–Gore-Tex®
–Teflon®

Sources
Widely available from multiple global suppliers.

Silicone

To discuss silicones is really to talk about a material enhancer and enabler rather than a specific material. Based on the crucial ingredient of silicon, which is one of the most abundant elements on earth, silicones add value to a whole range of applications that take advantage of its properties, which include temperature resistance and a warm, soft, rubbery tactile feel. One innovative product that makes full use of silicone's qualities is Sugru: this mouldable, self-setting product can be used to adapt existing products in a number of ways, as shown by the modification of a tool handle, opposite, to give it a non-slip, comfortable grip.

The extreme versatility of silicones means they can be formulated to deliver improved functionality in everything from inks and paints to fabrics, coatings and, of course, silicone rubber. Silicones can also be partnered with other materials for enhanced performance. In 1943, scientists at Corning Glass and Dow Chemical started producing silicone rubber made from carbon, hydrogen, oxygen and silicon. The material has a long list of impressive properties: it is incredibly flexible and tactile, and its appearance can vary from watery translucent tones to completely opaque colours; its working temperature range is phenomenal, extending all the way from -100°C (212°F) up to +250°C (482°F). Silicone is also chemically inert; which, coupled with its flexibility, makes it suitable for a range of medical applications, including prostheses and orthopaedic cushions.

Image: Sugra silicone rubber

+	–
–Extremely versatile –Excellent resistance to heat and chemicals –Wide range of production techniques –Widely available	–Comparatively expensive –Can be difficult to mould –Not recyclable

Production
Silicones can be injection moulded, extruded, calendared, blow moulded, rotational moulded and printed as inks.

Sustainability issues
Not recyclable or biodegradable, but is absorbed by solids in waste water treatment facilities.

Key features
- Difficult to mould
- Excellent chemical resistance
- Excellent heat resistance
- Excellent flexibility
- Readily accepts colour
- Comparatively expensive
- Shock absorbing
- Not recyclable

Sources
Widely available from multiple global suppliers.

Typical applications
The list of applications for silicones is vast depending on its form. It can be used as sealant in packaging as well as for bathroom sealant; it can be used as the basis for inks printed onto textiles that won't crack when stretched, and can be used for high temperature applications such as cooking dishes.

Cost
£5–12 ($8-19) per kg. depending on grade.

SMMA *(Styrene Methyl Methacrylate)*

Clarity is seductive. If you've ever seen glass making, you'll understand what I mean: solid, weighty clear globs blending, creasing, twisting and melting into each other in a mesmerizing way. But clarity can also be honest – everything is exposed behind a clear material. Apple used a translucent polycarbonate in the first iMacs to reveal the decorative potential of the technology behind the products, blending it with fun colours to mist some of the untidiness of the components. Look at the totally transparent dirt collector in a Dyson vacuum cleaner, which offers reassurance that your dirt is contained in the sealed container and your home is clean.

SMMA is from the styrenic family of polymers that includes polystyrene, ABS and SAN and is often seen as an alternative to the other clear plastics such as PMMA, PC, PET and SAN. An advantage of SMMA is its ease of processing and it therefore has a cost advantage over what might be its closest competitor, ultra clear acrylic. This is facilitated by the low melt processing temperature of SMMA and a lower mould temperature compared to tough materials such as PC and clear ABS.

The low density of SMMA means more parts per kilogram/pound of resin, and less post-moulding shrinkage results in less reworking of moulds. SMMA is noteworthy because it belongs in the category of transparent plastics and offers advantages in processing over the other transparent plastics.

Image: Brita water filter

+	–
–Excellent clarity	–Comparatively expensive
–Good for complex shapes	–Poor UV-resistance
–Takes colour well	
–Good chemical resistance	
–Approved for food use	
–Recyclable	

Production
SMMA can be processed like other thermoplastic materials by injection moulding, extrusion and blow moulding. Energy and labour costs can be lowered and cycle times can be increased by approximately 50% in comparison to other clear plastics because of the combination of lower mould and melt temperatures. It can also be welded using several methods such as hot plate, high-frequency or ultrasonic.

Sustainability issues
The faster cycle times, the lower density and the lower melt temperature of SMMA offers significant advantages in terms of embodied energy on SMMA.

Key features
- Versatile processing
- Excellent toughness
- Excellent clarity
- Colours and decorates easily
- Low density
- Good chemical resistance
- Food grade
- Recyclable

Cost
Comparatively inexpensive, often used as a cheaper replacement for acrylic.

Derivatives
–Acrystex®
–Zylar®

Sources
Widely available.

Typical applications
SMMA has its biggest markets in applications that combine clarity, toughness and complex shapes that need easy flow of the plastic.
On this basis, applications typically include tumblers with thin wall sections, perfume bottle caps with intricate shapes, handles for taps, water filter jugs, transparent coat hangers and a range of medical applications including surgical suction wands.

TPE *(Thermoplastic Elastomers)*

How many designers know exactly what a surface of Shore hardness 55A feels like? Or what a thermal conductivity of 0.18 W/mK means? A major problem designers face in understanding the differences between plastic materials is this abstract terminology. Plastics are named by chemists to classify a molecular structure, rather than reflect functions or uses. 'Thermoplastic elastomers', and the common abbreviation, TPE, doesn't communicate that this is a hugely versatile material, full of possibilities for designers to explore. TPEs are tactile, with a great rubbery grip; they are temperature-resistant, which makes them suitable for all sorts of cooking utensils; they are shock absorbing, which adds a premium robustness to products.

TPEs also fit well into the discussion about materials as a source of new consumer experiences. Contemporary industrial design is dominated by the desire to embed products with experiences that help to create new relationships between products and consumers. I love the OXO range of products, which make TPEs the hero in their range of products based on providing a good grip. These kinds of material experiences can strengthen a brand by enhancing the senses or by telling stories that relate to sustainability, indulgence or any other brand values.

Image: OXO GoodGrips® vegetable peeler

+	–
–Versatile –Good feel and grip –Flexible and tough –Shock absorbent –Widely available –Recyclable	–Relatively high cost of raw material –Less durable than competitive elastomers

Production
TPEs can be moulded using standard extruding, blow moulded, thermoformed and injection moulded. For this last method it is particularly relevant to consider two-shot mouldings and insert mouldings as a major use of TPEs. TPEs can be controlled to offer varying grades of hardness, anything from Shore hardness 55A, which is the same degree of hardness as the palm of a hand, to much firmer grades. They can also be used in modifying traditional thermoplastics, to improve impact strength.

Sustainability issues
Highly effective production means shorter production cycles, reduced energy consumption and minimal waste. Recyclable.

Key features
- Easy to colour match
- A seductive feel
- Excellent grip
- Excellent flexibility
- Shock-absorbing
- Relatively expensive
- UV-resistant
- Recyclable

Typical applications
TPEs have a wide variety of highly functional uses that range from seals on the inside of caps of drinks bottles and car windows, to packaging and grips on everything from power tools to toothbrushes.

Derivatives
–Monprene®
–Tekbond®
–Telcar®
–Elexar®
–Tekron®
–Hybrar®

Sources
Widely available from multiple global suppliers.

Cost
Relatively expensive: £13 ($20) per kg. However, the high cost of the raw materials can be offset by lower production costs.

UF *(Urea Formaldehyde)*

Solidity, being warm to the touch and high density are the characteristics that summarize the properties of urea formaldehyde. A nitrogen-rich waste product of urine, which, to produce a plastic compound, is condensed with formaldehyde. Part of this process yields a water-soluble liquid, which is used in adhesives and coatings, particularly in making pressed wood products such as medium-density fibreboard (MDF). The final part of the process yields a water- and chemical resistant resin for plastic moulding.

As a thermoset material it was one of the first materials to give Bakelite the shoulder because, unlike Bakelite, it could be moulded and produced in many more colour variations. Because of its heavy weight and general feel it has a high-perceived value. Urea-formaldehyde resin's attributes include high tensile strength, flexibility, and heat distortion temperature, low water absorption, high surface hardness, elongation at break, and volume resistance.

The toilet seat shown here is by Celmac, who utilize urea formaldehyde for its durable and resistant qualities, and also because it has the additional benefit of containing natural hygienic properties.

Image: Celmac toilet seat

+	–
–Good chemical-, stain-, and heat resistance –Hard and strong –Takes colour well –Cost-effective	–Not recyclable –In some applications, formaldehyde can be released into the air causing health problems

Production
As a moulding compound it is usually compression moulded. It can also be injection moulded to a limited degree, usually with fillers.

Sustainability issues
As with all thermosets, urea formaldehyde cannot be re-melted and re-moulded, so is not conventionally recyclable. Issues arose in previous decades with UF foam cavity wall insulation that was shown to be releasing formaldehyde into the air and causing health problems, but these days it is replaced with melamine formaldehyde and other low-emission UF insulation materials.

Sources
Available from multiple global suppliers.

Cost
Low cost relative to comparative thermosets such as melamine. £0.64 ($1) per kg.

Key features
- Excellent chemical resistance
- Excellent electrical insulation
- Easily coloured
- Excellent stain resistance
- Excellent heat resistance
- Warm to the touch
- Excellent hardness

Typical applications
Electrical switch plates, junction boxes, toilet seats, caps and closures for perfume bottles, buttons, adhesives and doorknobs. It can also be foamed for use as cavity insulation in buildings, and is used extensively in decorative laminates.

EPP *(Expanded Polypropylene Foam)*

Sitting snugly in the negative space between the cardboard box and the product lies a low-density and solid material that, though often used for packaging, has a much more valuable range of uses outside the short life of packaging.

The unique quality that expanded polypropylene has to offer the world of materials is its aerated structure, which can be controlled to a range of densities to achieve lightweight but thick, solid blocks. Its big disadvantage is that, like expanded polystyrene (EPS), its main application, and the one that is most visible, is in cheap, transient packaging materials. Although polystyrene and polypropylene are not the only materials that can be foamed, they deserve special attention because they are so prolifically used.

There are comparisons to be made between EPP and EPS, one of which is the ability they both have to be formed into large, solid wall thicknesses. EPP can also be coloured, printed with surface patterns, and graphics can be moulded into the surface. It can also be made available with different colour combinations in the same components, giving a mottled, multicoloured effect. Apart from stand-alone components and products, manufacturers have also developed technology where EPP can be moulded directly into the casings of other components, reducing assembly times and costs. EPS is much less brittle, offering a higher degree of flexibility, but can also be formulated to be much harder.

Image: GÜ packaging

+	–
–Inexpensive –Lightweight –Durable –Widely available –Recyclable	–Generates a lot of waste, which is difficult to dispose of

Production
The components are formed in male and female aluminium mould tools, with steam introduced from behind each half of the tool.

Sustainability issues
As with other aerated/expanded forms of plastics, the advantages they offer in relation to reduced use of materials is offset against the issue of the waste that these materials generate and the difficultly in disposing of such bulky items.

Cost
Comparatively low cost.

Sources
Widely available from multiple suppliers.

Typical applications
A good combination of properties make this prolific material useful for a massive range of applications, including surfboards and bicycle helmets, fruit and vegetable trays, insulation blocks, head impact protection in car head rests, bumper cores, steering column fillers and also acoustic dampening. EPP can also incorporate in-built springs for extra protection in packaging.

Key features
- Inexpensive
- Lightweight
- Excellent energy absorption
- Variable densities
- Good thermal insulation
- Can be coloured
- Recyclable

EPS *(Expanded Polystyrene)*

There are many materials that utilize air pockets as part of their structure; by doing so they reduce the quantity of material and so reduce the weight of that part. Clearly these qualities are valuable in reducing carbon footprints. However, the main issue with expanded polystyrene (EPS), approximately 98 per cent air, and expanded polypropylene (EPP) is that they are used as bulky packaging for transient types of products, which is extremely difficult to get rid of.

One way of looking at this issue is to look at the timespan of the usage against the time it takes to make the oil/plastic and the time it will take the plastic to degrade. For example, it takes millions of years to produce the ingredients from which petroleum-based plastics are derived, and sandwiched between that and the hundreds of years that they take to fully degrade is a microscopically small amount of time in which the products are actually used. A lot of valuable and limited materials are used to produce something that has a very short lifespan and then is just thrown away.

However, these foams can have a much richer range of potential applications than we might assume. The advantage they can bring to more long-term use products is that they are very lightweight and, because they are foams, use very little raw material compared to solid mouldings of plastics. As the basis for ABS, SAN, ASA and HIPS, polystyrene belongs to the styrene family of polymers, which is a naturally occurring substance found in the environment.

Image: Tom Dixon's EPS chairs

+	–
–Inexpensive –Lightweight –Shock absorbent –Offers good insulation –Recyclable	–Perceived as being environmentally unfriendly –Not especially strong or flexible

Production
Polystyrene foam production is based on tiny polystyrene beads that are expanded to 40 times their original size using steam and pentane. Steam is then used in the final phase to inject the material into the mould. Polystyrene is much less of a performance material than EPP, not having its range of densities, flexibility and strength. In other forms, foamed polystyrene is extruded and thermoformed into trays. Like EPP, components are formed in aluminium male and female mould tools with steam introduced from behind each half of the tool.

Sustainability issues
Although 98% air, it is often viewed as not being environmentally friendly. However, polystyrene foam has never used CFCs or HCFCs during production. The perception of bulky packaging not being recycled but left to accumulate enforces the perception of the material being unenvironmental. As a result, big steps have taken place in the last few years to provide recycling facilities. Once collected, the waste is compacted and remoulded in its compacted form or ground down to be used in new products.

Key features
- Inexpensive
- Lightweight
- Good insulation properties
- Good thermal insulation
- Cushioning
- Recyclable

Cost
Low cost: £1.30 ($2) per kg.

Typical applications
Historically found in disposable drinking cups and food trays (although now often replaced by laminated paper) and in packing. Expanded polystyrene has also been used on a much larger scale in housing. In the Netherlands it has been used as a buoyant platform and a house in the UK has been made entirely of expanded polystyrene. In horticultural applications it is used to control temperature around root growth.

Sources
Widely available from multiple suppliers.

PE *(Polyethylene)*

Polyethylene – the material from which Tupperware is made – has changed the way people stored and transported food forever. Tupperware consisted of lightweight, tough containers with lids that had air-sealing properties. When you pushed down the lid you would expel the air, creating a small vacuum in the container, and the removal of air kept food fresh for longer. This was a difficult concept to communicate effectively on packaging, and so gave rise to the home demonstration and the christening of the 'burp', the sound of the air being drawn into the container. Imagine, the sound of a material leading a marketing campaign.

Polyethylenes are the most widely used plastics worldwide, and one of the hardest to summarize, simply because they have so many different varieties. Some are soft and waxy while others are stiff; some are strong with high impact strengths while others are easily breakable. However, the typical characteristics that designers should know about are: good chemical resistance (think of the engine oil bottles you buy from the garage); they are tough, which is why children's toys are often made from polyethylene; they have low friction and low water absorption; they are cheap and very easy to process. These last qualities mean polyethylenes have been used to make everything from the original Hula-Hoop and Frisbee to another type of American icon, Tupperware.

Image: Polyethylene traffic cone

+	–
–Low cost –Easy to process –Versatile –Tough –Recyclable	–Not readily biodegradable

Production
As with many commodity thermoplastics, PE can be formed using a number of methods. The most common are probably rotational moulding and blow moulding.

Sustainability issues
PE is one of the most widely recycled plastics. The nature of thermoplastics – materials that soften when reheated – means that all of the materials featured here are recyclable. As with any issue concerning the environment there are many factors to consider, one of which is the ability of single materials to be separated from each other. HDPE is identified by the number 2 in the recycling symbol and LDPE by the number 4.

Typical applications
A number of large-scale children's toys are made from HDPE. Other products include chemical drums, household and kitchenware, cable insulation, carrier bags, car fuel tanks, furniture and the iconic Tupperware.

Key features
- Versatile processing
- Waxy surface
- Low friction
- Excellent chemical resistance
- Springy toughness
- Easy to colour match
- Recyclable

Cost
Rotational moulding HDPE is only slightly more expensive than bottle grade PET.

Derivatives
–PET (Polyethylene terephthalate) commonly know as polyester
–LDPE (low-density polyethylene)
–HDPE (high-density polyethylene)
–MDPE (medium-density polyethylene)
–ULDPE (ultra low-density polyethylene)
–LLDPE (linear low-density polyethylene)

Sources
Widely available from multiple global suppliers.

PET *(Polyethylene Terephthalate, aka Polythene)*

From carpets to cosmetics, PET is everywhere. Clear and tough, it is one of the standard materials for hundreds of types of products. Part of the polyester family, which also includes PBT and PETG, it is crystal clear and impervious to water and CO_2, which makes it ideal for packaging fizzy drinks. In these applications it is often extruded with other materials to form material sandwiches to increase its properties, for example in packaging beer, where oxygen scavenging layers are used in between the PET to stop oxygen getting in or out.

Since the early 1970s, when the first PET bottle was patented, there have been other developments, including the use of a green colouring system that borrows the concept of chlorophyll from nature and is introduced to the material to act as a UV light blocker, which increases the longevity of the contents. This is an improvement on the use of the traditional brown colour, which obscures the contents and has connotations with medicine bottles. The chair shown here was a collaboration between Coca-Cola and Emeco and was made from 111 recycled PET bottles.

Image: 111 NAVY® chair by Coca-Cola and Emeco

+	–
–Low cost –Tough and durable –Versatile –Excellent stability –Resistant to chemicals –Recyclable	–Can suffer from negative associations of cheapness –Not readily biodegradable

Production
As with other thermoplastics, PET can be injection moulded, extruded and, as the number of bottles demonstrates, blow moulded. It can also be calendered into sheets.

Sustainability issues
In terms of the material, PETs represent one of the biggest areas of recycling, with the bottles being re-melted to make carpets, fibres, video cassette tape and as a filler for pillows and clothes: five two-litre PET bottles can yield enough fibrefill to make a ski jacket. PET is identified by the number 1 in the recycling symbol.

Typical applications
Apart from food, drinks, household cleaning products and cosmetic packaging, other applications for PET include display and decorative film, credit cards, clothing and even car body panels and ten-pin bowling balls.

Cost
£1.30 ($2) per kg.

Sources
Widely available from multiple global suppliers in both virgin and recycled forms.

Key features
- Excellent chemical resistance
- Excellent dimensional stability
- Tough and durable
- Inexpensive
- Excellent clarity
- Good impact strength
- Recyclable

Derivatives
–One of the most recent innovations in PET is from Sidel who have produced NoBottle™, a 500 ml bottle weighing 25-40% less than a conventional bottle.
–Mylar® and Melinex®

PMMA *(Polymethyl Methacrylate, aka acrylic)*

When plastics were first commercialized though mass-production, one of the really special, exciting and unique qualities that must have captured people's imaginations was not only the idea that you could mould a material into virtually any shape but that you could even make it look like glass. This must have offered designers a great new tool to create luxuriously clear products that could capture the imagination of consumers. Today, transparency is still a visual quality that very much suggests high value. One of the clearest and most widely available clear materials is polymethyl methacrylate.

It's also a material with many incarnations, one of which is in a household name, Perspex, which is a sheet material. PMMA is visually hard to distinguish from its slightly less clear but tougher relative, polycarbonate, and although it is less temperature resistant it is still in relatively the same region for pricing. Unless blended with other plastics like PVC, which improves its impact strength, polymethyl methacrylate does share a degree of the fragility of glass. There other materials like polystyrene, polycarbonate, PET and SAN that compete for clarity, but acrylic falls between polystyrene and polycarbonate for cost.

Image: Standing Ovation cutlery by Giulio Iacchetti

+	–
–Highly versatile	–Poor solvent resistance
–Hard and stiff	–Not very hardwearing
–Widely available	
–Excellent clarity	
–Recyclable	

Production
In its granular form, PMMA is a versatile thermoplastic that can be injection moulded and extruded. It is also widely available in a range of semi-finished rods, tubes and particularly sheets.

Sustainability issues
Petroleum-based so not the most sustainable choice. However PMMA can be reground, melted and extruded into new products.

Typical applications
One of the first commercial outings for PMMA was a canopy for the cockpit of fighter aircraft in World War II. Today, apart from its use in paints and fabrics, acrylic is readily available as rod or tube, or as cast and extruded sheet, where it is used in furniture, glazing and interior screens. As a moulded material it is used in lenses, signage, car taillights, furniture and drafting equipment.

Cost
£2.55 ($4) per kg.

Derivatives
–Apart from its Sources as a resin it is also a hugely popular sheet material sold under the Perspex®, Plexiglas®, Lucite® and Acrylite® trade names.
–Acrylic is also the main ingredient for Dupont's solid surface material Corian®.

Key features
- Excellent clarity
- Good hardness
- Good stiffness
- Resistant to weathering
- Easy to colour match
- High print adhesion
- Poor solvent resistance
- Poor fatigue resistance
- Recyclable

Sources
Widely available from multiple global suppliers.

PP *(Polypropylene)*

Polypropylene is possibly one of the most recognizable plastics due to the trend, begun in the 1990s, for using it in all kinds of coloured, matt translucent products. It's also one the easiest plastics to identify and remember: just think of the waxy feel of PP on the butterfly hinge on a toothpaste tube – PP is the best commodity plastic for withstanding repeated bending.

This, and its ability to be coloured are two of its key characteristics. It also performs well at high temperatures, but less well at low temperatures. It has good toughness, chemical resistance and the ability to create a built in 'live hinge', as on the toothpaste cap, which opens hundreds of times without shearing. It is, like other commodity plastics such as polyethylene and polystyrene, highly cost effective, which means it is used prolifically in all levels of consumer products, particularly in the billion plastic baskets that are sold every day at shops across the globe.

Polypropylene has similar properties to polyethylene, but a lower density and higher softening point of 160°C (320°F), compared with 100°C (212°F) for PE. It differs from PE in that it has only one main form; however, it is available in different grades, such as one that changes it from its naturally milky appearance into a version that is closer to crystal clear PET. Polypropylene is particularly good at receiving glass-fibre reinforcement to give it superior strength and rigidity, which makes it ideal for large-scale applications such as furniture.

Image: Chop2Pot by Joseph and Joseph

+	–
–Versatile, easy to work –Can withstand repeated bending –Tough and resistant –Colourfast –Recyclable	–Poor UV resistance: additives required for external applications

Production
As a commodity plastic it can be widely processed through a variety of techniques including injection moulding, thermoforming and foaming extrusion. In extruded sheet form it can be die-cut, folded and creased. Moulded PP also readily accepts fillers and reinforcement such as minerals and glass for increased stiffness.

Sustainability issues
As one of the main commodity plastics, it occupies number 5 in the recycling triangle symbol and as such can be recycled where an effective recycling programme is in place.

Cost
£1.55 ($2.45) per kg.

Key features
- Versatile processing
- Good high-temperature resistance
- Tough
- Inexpensive
- Blends well with other materials
- Excellent flex resistance
- Food grade
- Good chemical resistance
- Accepts filler and reinforcements
- Recyclable

Derivatives
–EPP (Expanded Polypropylene)
–Curv® self reinforced PP from PropexFabrics.com

Sources
Widely available from multiple global suppliers.

Typical applications
It is used for anything that displays a durable, live hinge, such as toothpaste tube lids, through to packaging for fast food that can be placed in a microwave.

PUR *(Polyurethanes, aka Urethanes, Polyurethane Rubber)*

The unique thing about plastics is that, having such vastly differing properties, they can be applied to every conceivable type of product. Unlike a carpenter or ceramicist, who works directly with their materials, the problem for a product- or industrial designer who works with plastics is that to really understand the different grades, they will have to go through the entire process of specifying, using and applying these materials. I will try to simplify this large family.

Urethanes are one of the five major groups of polymer classifications; the others are ethylenes, styrenes, vinyl chlorides and esters. Part of the reason they can be converted into so many different forms is that, like PVC, they can be produced as thermosets, thermoplastics and in rubbery forms. The versatility of polyurethanes means that there are many forms and grades that can be specified. These can be split into three broad areas, which are coatings, rigid and flexible foams, and rubbers. In the context of design, the most useful form is rubbers, or PUs, for their high abrasion resistance and overall toughness.

In terms of abrasion resistance, they can be compared with Nylons and acetals, with some elastomeric forms of polyurethanes being 20 times more resistant to scratching than metals. In terms of flexibility, they are similar to TPEs but without the adaptability of a range of moulding techniques; however, they are much less expensive than silicones or EVAs.

Image: Mesa Table by Zaha Hadid and Patrik Schumacher

+	–
–Widely available –Enormous range of applications –Strong and resistant –Hardwearing	–Understanding the different grades of this vast materials family can be a minefield –Not generally recyclable

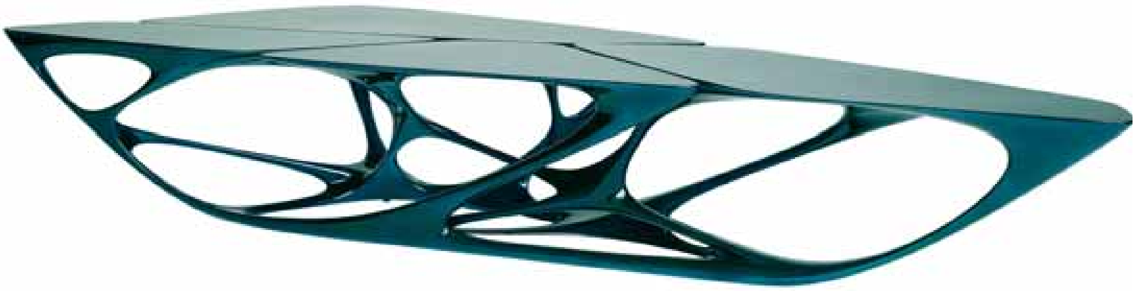
Production
In order to understand the processing of PUs, the various forms need to be understood. As a thermoset material – foams – it is limited to reaction injection moulding. As a TPU, it is suitable for a range of production methods, including injection moulding, compression moulding, casting, extrusion and also spraying.

Key features

- Excellent tensile strength
- Excellent toughness
- Excellent flexibility
- Excellent abrasion resistance
- Excellent cut resistance
- Excellent chemical resistance
- Good resistance to weathering
- High flex life
- Good impact strength
- Generally not recyclable

Cost
TPU: £2.55 ($4) per kg.

Sources
Widely available from multiple global suppliers.



Sustainability issues
Low temperature moulding saves energy and is the most common form of reusing PUs. Low temperature moulding is when the material is re-ground and bound together.

Derivatives
–Polyurethane foams
–Memory foams
–Spandex® and Lycra®

Typical applications
PU foams are used as insulation in buildings, and in a different form as furniture cushioning and bed mattresses. In its rubber form, it is used in squeegee blades, vandal-proof street bollards, rollers for castor wheels, springs and shock absorbers. In consumer applications it is used for the soles of running shoes and shoe heels, fabric coatings and furniture.

PVA *(Polyvinyl Alcohol)*

PVA is the plastic that most of us are likely to have encountered as a silky water-based white wood glue. In the context of designing with polyvinyl alcohol, as well as its use as an adhesive, its other main use is still in liquid form but for coatings for papers, textiles and finishing for leather. In terms of use for three-dimensional mouldings, it is limited due to its water solubility.

There are a few suppliers who sell polyvinyl alcohol-based resins, but one of the most interesting examples is its availability as a water-soluble yarn. The dissolving process, which can be set to activate at any temperature from 30–95°C (86–203°F), also leads to another unique property. During the process, the fibres will shrink by 50 per cent before they dissolve. This quality is useful in the textile industry where this fibre, one brand name is Solvron®, can be added to textiles where a mechanical pulling force is needed, in items such as filters and medical bandages, but it is also used as a sacrificial material during the production of garments.

The world is filled with many natural fibres – an area that is growing rapidly – and synthetic fibres that are leading to some incredible, smart textiles. However, what's interesting with PVA yarns is that they perform a smart function with a fairly low-key and biodegradable ingredient as its basis.

Image: Laundry tablets with PVA capusule

+	–
–Biodegradable –Water soluble –High tensile strength –Light polarization qualities	–Limited availability compared to other plastics

Production
The moulding of polyvinyl alcohol through melting is difficult because the melting point and degradation temperature are very close. However, some suppliers offer pelletized polyvinyl alcohol, which can be processed with conventional plastic technology, such as blown and flat-film extrusion as well as injection moulding. It can also be used as an additive to enhance biodegradable materials due to its own water-soluble properties.

Sustainability issues
The environmental benefits of PVA are clear: it is biodegradable and water-soluble.

Key features

- Water-soluble
- Biodegradable
- Low ash content
- High tensile strength
- Polarizes light

Cost

£0.75 ($1.20) per kg.

Sources

PVA in a mouldable form has limited availability compared to many other plastics.

Typical applications

Apart from adhesives and yarn, the water-solubility of PVA has resulted in a range of plastic films for packaging. One area it is used in is fishing, where bait is put into PVA bags and then into the water, this allows a concentration of bait in the water while the bag itself dissolves. This same principle is exploited in laundry tablets, where a liquid detergent is enclosed within PVA capsules that then dissolve in the machine. The crystalline structure of PVA allows it to polarize light leading to applications for light filters such as dichroic polarizers.

Derivatives

–Solvron®
–Mowiol®
–Poval®
–Mowiflex®

PVC *(Polyvinyl Chloride)*

Put bluntly, PVC smells like sick. It is inexpensive and is often used as a cheap replacement for natural materials, such as imitation leather, but it is one of the most widely used plastics in the world. It's found in everything from credit cards to roof membranes and has come to define cheapness, and in recent years has been considered a generally unhealthy plastic.

One of the reasons for its widespread use is that, like polyurethanes, PVC is extremely versatile and can be produced as thermosets, thermoplastics and in elastomeric forms. These range from a powdery, dry feeling PVC to the rubbery stickiness of a child's swimming inflatable. Another reason for the popularity of PVC is its low cost and the stability of its price, due to 50 per cent of its make-up coming from non-petroleum based sources. This and ease of processing means that it was one of the most widely used plastics in the world until the 1980s, when it became the poster boy for how bad plastics are.

Industry is still divided regarding the health and environmental damage that PVC causes, but the concerns are detailed in the box on the right. The PVC industry's defence lays in what they claim is the low level of risk and likely exposure to these substances and the fact that PVC has been used in the medical industry for many years for blood bags, where the use of plasticizers have actually been shown to extend the shelf life of blood.

Image: PVC soap dish

+	–
–Extremely versatile –Good chemical resistance –Widely available –Low cost –Hard wearing –Recyclable	–Health concerns over its production and disposal –Negative associations of cheapness –Poor UV resistance

Production
The variety of processing techniques is one the reasons that PVC is so widely used. Apart from extrusion, rotational moulding, injection moulding, blow moulding and calendering, it is also used for dip moulding. Varying the amount of plasticizer gives flexibility in moulding, with stretch PVC sheet containing large amounts of plasticizer. In sheet form it is also conducive to being ultrasonic and high frequency welded.

Sustainability issues
Dioxins are emitted when PVC is produced, melted for recycling and incinerated, largely because of a chlorine compound that is a large part of its composition. Unlike many other plastics, PVC is based on approximately 50% petrochemicals, the rest is made of a chlorine-based compound. This means PVC is more stable price wise.

The second environmental issue is the use of stabilizers and plasticizers in the production of the material. In terms of function, stabilizers are used to impede degradation and plasticizers to increase flexibility. Both of these additives have problems. Stabilizers use heavy metals like lead and barium and the plasticizers contain hormone disrupters. There are moves to reduce these problems by the manufacturers who, through various means, can reduce the amount of dioxins being produced and also use organic stabilizers.

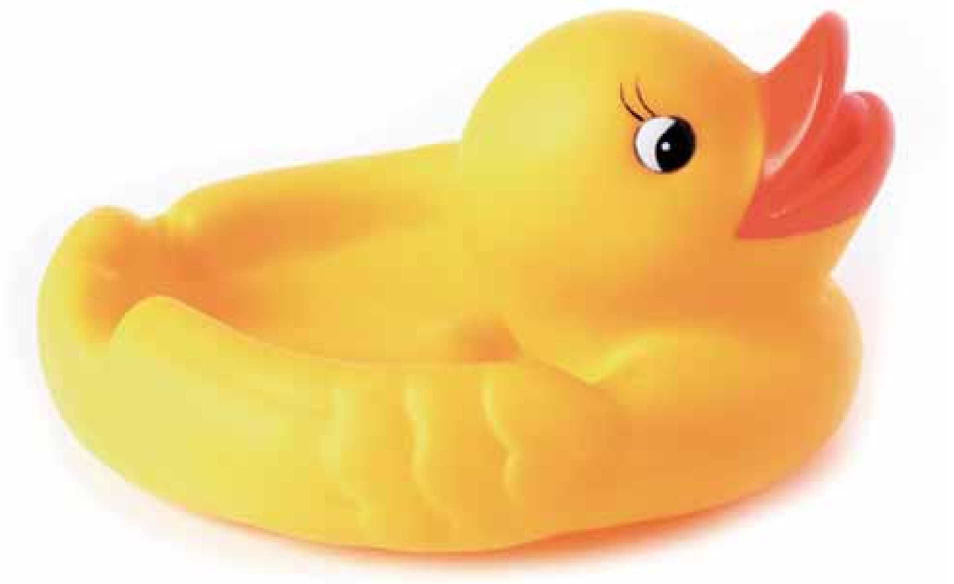
PVC is identified by the number 3 on the recycling symbol.

Key features

- Versatile processing
- Inexpensive
- Easy to colour
- Blends well with other materials
- Good chemical resistance
- Good electrical resistance
- Multiple forms/grades
- Not naturally UV resistant
- Environmental concerns
- Recyclable

Sources

Widely available from multiple global suppliers.



Typical applications

It is difficult to summarize the versatility of this material. However, applications include dip-moulded bicycle handles, fake leather, garden hoses, drain pipes, flooring, electrical cabling, 'artificial skin' used in burns treatment, sun visors, raincoats, credit cards and inflatable toys. Unplasticized, or rigid, PVC (PVC-U) is used extensively in building applications such as window frames.

Cost

£0.65 ($1) per kg.

MINED

From shape-memory metal alloys and contemporary interpretations of classical marble through to advanced flexible and lightweight glass and advanced ceramics, this section is possibly the most diverse in its scope. Organized into sub-categories of metals, glasses and ceramics, it encompasses major materials that are extracted from the earth. If there were anything that tied these materials together it would be the associations they embody, due to their long established applications dating back to Iron and Bronze ages.

With so many varieties and applications, ceramics are difficult to define and are used in a multitude of product areas that range from house bricks to teacups, from bulletproof vests to kitchen knives for carving the Sunday roast. Malleable and pliable, they can be pushed and pulled, squeezed and moulded, poured and ground: they can be the most immediate and simple material to form, but at the same time highly precise and shockingly hard. Starting out as a clammy, wet, cold lump, they can become a material with the most enduring of physical properties. Their versatility is such that they can be played with in the school classroom and also used in advanced applications and extreme environments like the tiles in the space shuttle. Then there is glass: 180 parts sand, 180 parts ash from marine plants and five parts chalk, melted together to produce an amazing liquid. The glass family is also undergoing an enormous change, with new forms of ultra-thin glass being developed, such as Gorilla® Glass from Corning®, which in our screen-based digital age is the material that is facilitating all the information that we are receiving.

Then there are the metals. About three quarters of the elements in the periodic table are metals, about half of which are commercially important, and from these elements we have managed to cook up at least 10,000 different varieties of alloys, such as stainless steel, where a combination of iron, chromium and nickel demonstrates a partnership where each material brings its own characteristics, turning plain carbon steel into a harder non-rusting alternative.

Gold *(Au)*

Gold has to be one of the most significant materials in history, both culturally and economically. A malleable and dense material that, together with copper, silver, lead, tin, iron and mercury, was alone in the known metals family for 7,700 years. Without exception, it is the only metal in the metals family that is chemically stable, all the others react with oxygen and other elements to corrode.

Gold has never really been an industrial designer's material. Naturally, jewellery designers use gold all the time, but outside of jewellery any reference to gold in design can be seen as intentionally kitsch or perhaps seen as overdoing it slightly. As a benchmark of value and luxury and a status symbol, gold is unique in the sense that it has not been replaced by more contemporary synthetic materials, such as carbon fibre or titanium, two materials that always crop up in luxury brands. Use it even in the smallest quantity and it instantly creates an air of luxury for a product. The purity of gold is measured in carats. Twenty-four carat is pure gold, 18 carat refers to a purity that is 18 parts gold out of 24, or 75 per cent pure gold.

Gold is extremely malleable and can easily be beaten into incredible, translucently thin sheets. An example of this is seen in the fact that just 28 grams (1 oz) of gold can be worked into a flat leaf covering 16 square metres (172 square feet); one of the reasons it has been so well worked and applied in jewellery for thousands of years.

Image: Gold Pill by Tobia Wong

+	–
–Extremely malleable –Excellent conductor of heat and electricity –Biocompatible –Corrosion resistant –Recyclable	–Rarity and expense limits use –Environmental/ethical issues around mining

Production
As with other metals, gold can be cast using a variety of techniques. It can also be used for gilding and to electroplate. It can be beaten, woven into thread and used to make gold leaf.

Sustainability issues
Apart from its rarity in nature, the main issues with gold appear to be in mining it and ensuring mines and mining countries have ethical policies. A significant proportion of mining of gold takes place in developing countries and the impact of mining is significant in these fragile economies. Safe working conditions, production of toxic waste, non-use of mines not in protected areas and dumping of mining waste are all considerations for sourcing gold ethically. One example is the use of highly toxic mercury to extract gold from its ore. Here, the gold is picked up by the mercury, which is then eventually boiled off to leave the gold. On a positive note, 28 g (1 oz) of gold can cover 92 square metres (1000 square feet) of glass, in this instance it can be energy efficient in reducing cooling costs in a building, due to its ability to deflect the sun. At the end of 1999 the World Gold Council estimated that all the gold that had ever been mined would create a cube 19.35 metres (63 feet) on each side, or enough to fill 125 double-decker London buses.

Key features
- Extremely malleable
- Corrosion resistant
- Does not oxidize
- Biocompatible
- Capable of good surface finish
- High thermal conductivity
- High electrical conductor
- Recyclable

Sources
China, followed by Australia and the US, is the biggest producer of gold. Other major producers include Indonesia, Peru, Russia and Ghana.

Typical applications
Apart from jewellery and surface decoration, gold is used as an alloy in dentistry for dental restorations. The electronics industry use gold-plated contacts and connectors in applications where silver and copper are not as tarnish resistant. It is used in biomedical devices and nanotechnology, which exploit its corrosion resistance. It is also used as coatings for glazing to reduce the transmission of heat.

Cost
£33,245 ($52,000) per kg.

Silver *(Ag)*

As a very soft metal, silver is only used in its pure form for plating. To make it more durable for making jewellery and cutlery it is alloyed with copper to produce sterling silver (92.5 per cent silver and 7.5 per cent copper), which adds hardness. It is easy to think of silver as a material used mainly for jewellery, but it does in fact have some surprisingly unique and outstanding properties, which are exploited in a range of less familiar industries. For example, historically, silver was used to detect poison in food, with silver cutlery used to indicate if poison was present because the silver would turn black if it reacted with arsenic.

But it's not just the fact that it tarnishes and its reactions to chemicals that make silver useful, it is also the most efficient conductor of electricity and has a high reflectivity of light, which means it is often partnered with glass for mirrors: mirrors, windows for reflecting heat and light, and light-reactive prescription sunglasses all utilize this feature of silver. This unique ability to react to light also accounts for what used to be one of its main market areas: traditional photography. Silver has a unique ability to react to light, forming latent images that can be developed later to produce photographs. However, with the decline of traditional photography one of the growth areas for silver is in antimicrobial applications, where it is used to control odour in a range of wearable applications, it is also used to regulate body heat.

Caption: Silvered brass centrepiece, Chitai Mann Singh

+	–
–Excellent electrical and thermal conductivity –Light sensitive –Malleable and ductile –Highly decorative –Antibacterial –Recyclable	–Sensitive to discolouration –Easily tarnishes

Production
The ductility of silver is one of the reasons it has such widespread use in jewellery; it can be easily formed by cold working, annealing, extrusion and also various casting methods, such as lost-wax casting.

Sustainability issues
Silver is not known to be harmful to the body in any way, and its ability to inhibit bacterial growth can be seen as a benefit. Silver is the main active ingredient in photovoltaic cells and therefore contributes to non-petroleum based fuel. It is also used in glazing, where silver coatings reduce the amount of UV light that penetrates the glass.

Derivatives
–Sterling silver (silver, copper)
–Electrum (silver, gold)
–Amalgam (silver, mercury)
–Britannia silver (silver, copper)
–Argentium sterling silver (silver, copper, germanium)
–Billon (copper or copper bronze, sometimes with silver)
–Goloid (silver, copper, gold)
–Platinum sterling (silver, platinum)
–Shibuichi (silver, copper)

Key features
- Outstanding electrical conductivity
- Capable of good surface finish
- Outstanding thermal conductivity
- Easily tarnishes
- High sensitivity to light
- High sensitivity to discolouration
- Very malleable and ductile
- Corrosion resistant
- Antibacterial
- Recyclable

Typical applications
Silver is mainly used in the jewellery, industrial and photographic industries. It has the highest conductivity of any metal, so is used in the electronics industry to produce solders. Its ability to react to light is exploited in producing photographs, and a large proportion of the total use of silver in the USA is in this area. It is widely used as a plating material, and also provides excellent electromagnetic field (EMF) shielding.

Sources
Mexico and China are two of the biggest producers of silver, accounting for around one third of global production. World reserves are estimated to be in the region of 530,000 tonnes.

Cost
£620 ($970) per kg.

Platinum *(Pt)*

Materials develop value in a number of ways: through association; through weight and heaviness; through age; through production; and through context. Metals can more easily assign high values to products than high-tech composites or smart materials. From fountain pen nibs to computer disks, platinum has many more uses than just jewellery. As part of the precious metal group, this soft, white, ductile material has its own family of platinum-group metals, which includes palladium, iridium, rhodium, ruthenium and osmium.

Platinum is more ductile than silver, copper or gold but heavier than gold. Like gold, platinum is highly malleable, and just one gram can be made into a piece of wire one mile long. Its use in jewellery is due to its density, hardness, strength and oxidation resistance, which makes it a suitable material for settings for precious stones. As a ductile material, platinum is often alloyed to increase hardness.

As with many metals, platinum has a biological function; one of the lesser-known uses for this precious metal is in cancer treatment, where it can inhibit the growth of cancerous cells.

The nibs of Montblanc pens are made from 18 carat solid gold, which was originally used because it resisted the chemicals used in the early inks. Today, it's used for its prestige and ability to flex and spring when writing. However, the softness of gold would result in the nib wearing quickly, therefore the tip is made from iridium, an extremely hard material.

Image: Montblanc pen nib

+	–
–Ductile –Highly decorative –Excellent heat resistance –Biocompatible –Corrosion resistant –Recyclable	–Relatively expensive so use limited to high-value items

Production
While there is some open-pit mining, most platinum mining takes place underground and extraction is labour-intensive, as miners must bore holes and then blast with explosives to obtain the ore. Like silver, platinum can be cold worked, annealed, extruded and cast.

Sustainability issues
Platinum is not harmful and is non-toxic.

Key features
- Ductile
- High density
- Good surface finish
- Does not oxidize
- Excellent chemical resistance
- Excellent corrosion resistance
- Biocompatible
- High melting point 1768.3°C (3214°F)
- Recyclable

Typical applications
Platinum is best known for its use in jewellery; however this only accounts for about 38% of its applications. It is used in many industrial applications, including catalytic converters. It is also used in fountain pens, which exploit its hardness; aircraft spark plugs, which exploit its high resistance to heat and high conductivity; as an alloy for coating shaving blades; and in electrical contacts and resistance wire. Because of its high resistance to corrosion in the atmosphere, it is used as a coating on components. Other alloys are used for dental restoration, where it is mixed with gold or silver as well as copper and zinc. Adding platinum to computer hard discs enhances the magnetic qualities, allowing more data to be stored. Platinum is also biocompatible and used in surgery.

Sources
South Africa is the world's biggest producer of platinum, accounting for more than half of global output, which, in 2012, was 192,000 kg (423,288 lb). World reserves are currently estimated at 66,000,000 kg (933,190 lb).

Cost
£30,047 ($47,000) per kg.

Brass & Bronze

Brass is a material that is trapped in a cultural time warp. Think of brass and you don't think of modern aesthetics or materials that fulfil specific needs in contemporary life. Instead, the metal with a colour of warm brown sugar suggests an ancient time, where the acoustic properties of cartridge brass were utilized to make a huge range of musical instruments, from bells to trumpets. Like silver, its oxidation and subsequent need to be polished also creates satisfying rituals around the use of this metal.

Straightforward brass is approximately 65 per cent copper with no more than 40 per cent zinc. Like many other metals, brass is not a single material but a vast family, each with differing properties. Some of the brasses in this group include jewellery bronze, red brass, yellow brass and gilding metal. Other main brass groups include leaded brass, casting brasses and tin brasses. Some brasses are known as bronzes, this is a term that usually applies to copper alloys, which have a main alloying element of tin or zinc. Bronze used for casting statues has approximately 10 per cent tin, about half the amount used for tougher engineering applications such as turbine blades. The addition of tin produces harder and stronger materials.

Image: Studio Job Bottle Rack vase

+	—
–Excellent for casting –Suits a variety of production methods –Radiation resistant –Strong and ductile –Recyclable	–Can suffer from 'old-fashioned' associations –Welding can be difficult due to the zinc content

Production
Brass can be cast using various methods including sand and die-casting. Bronze in particular is a great material for casting due to its low viscosity, which allows it to flow into complex shapes with fine details. It can also be forged, extruded, applied as a coating using the electroforming process and is readily available in sheet, rod, tubing and solid forms, where it can be die-stamped, rolled, press-formed, machined, impact extruded and spun. In terms of joining, brass can be soldered, brazed and welded (although welding is not straightforward).

Sustainability issues
Brass is often made from recycled scrap, to the point that in the UK brass manufacturers use almost 100% brass scrap. As one the main ingredients of brass, copper production amounts to approximately 16 million tonnes a year and exploitable reserves are around 690 million tonnes. Also, according to the US Geological Survey in 2011, zinc production was around 12,000 tonnes per year with current reserves at 250,000 tonnes.

Derivatives
–Nickel silver brass
–Aluminium bronze
–Silicone bronze
–Manganese bronze

Key features
- Excellent corrosion resistance
- Good strength and ductility
- Versatile processing
- Inexpensive (cheaper than copper)
- Very good electrical conductivity
- Good machinability
- Antimicrobial
- Resistant to nuclear radiation
- Recyclable

Sources
Brass and bronze consist mainly of copper and Chile is one of the major sources.

Typical applications
Brass alloys are used in a large range of applications including electric plugs, lightbulb fittings, medical instruments, cable glands, bearings, gearwheels, household and plumbing fittings, aircraft, train and car components. A common application of brass is in wood screws, which take advantage of its excellent corrosion resistance. As with copper, it's used in applications where antimicrobial properties are required, particularly in hospitals.

Cost
£2.50 ($3.85) per kg.

Copper *(Cu)*

Copper is characterized by its rich, auburn colour, which perhaps does not fit with contemporary visual language trends, where technology increasingly requires brighter, whiter metals. However, from a cultural perspective, copper has been instrumental in many aspects of human evolution since it was first used, approximately 10,000 years ago.

Copper's versatility is demonstrated in many of the elements that humans need to survive: food, power, shelter and water. It is of such importance that in the periods of history when materials were used to define human evolution it had its own period, the Chalcolithic period, a phase of the Bronze Age. However, one of the beautiful things about copper is that it's a raw ingredient, which, through pairing with other metals, can be tailored to specific properties for far reaching applications. For example, blending it with tin will give you bronze and blending it with zinc will give you brass. Beyond that, it can be mixed with nickel, beryllium and aluminium to provide other variations of copper. This versatility and the fact that it leads to over 400 alloys gives an understanding that copper is close to having its own material family.

Today, one of the major uses of copper is as an electrical conductor. Along with silver, copper has by far the highest thermal conductivity rating – the speed at which heat or cold are transmitted through a material – of any material, the main reason it feels cold to the touch.

Image: Spun Chair, Thomas Heatherwick

+	–
–Versatile –Excellent finish –Tough –Excellent electrical and thermal conductor –Recyclable	–Like brass, copper can suffer from old-fashioned associations

Production
Copper is a great material for casting due to its low viscosity, which allows it to flow into complex shapes with fine details. It can be cast using various methods including sand and die-casting. It can also be forged, extruded, applied as a coating using electrolysis and is readily available in sheets, rods, strips and solid forms where it can be die-stamped, rolled, press-formed and machined.

Sustainability issues
Its usefulness and proliferation are largely due to the ease with which it can be mined and separated from its ores. Copper deposits are found far and wide in the environment due to the ease with which it attaches to organic matter and minerals. According to the US Geological Survey in 2011, world production of copper amounted to approximately 16 million tonnes a year and exploitable reserves stood at around 690 million tonnes.

Key features
- Good resistance to corrosion
- Ductile and malleable so easy to work
- Excellent electrical and thermal conductor
- Tough
- Alloys well with other metals
- Antimicrobial
- Capable of good surface finish
- Recyclable

Sources
Although copper can be found freely in nature, the most important sources are the minerals cuprite, malachite, azurite, chalcopyrite and bornite. Approximately 90% of the world's primary copper originates in sulphide ores. Major sources of copper are Chile and China.

Cost
£4.50 ($7) per kg.

Derivatives
–Gunmetal
–Copper-Nickel
–Non-electrical copper
–Machining copper
–High strength alloys
–Electrical copper

Typical applications
It is impossible to list all the areas for which copper has been used, but they include roofing, wire for carrying electricity and motor windings, carrying water, cooking and jewellery. It is also the basis for brass and bronze. One of the most interesting applications might be the use of copper fibres in socks, where it is used to reduce odours due to its antimicrobial properties.

Chromium *(Cr)*

The most distinguishing feature of chromium is that it is shiny, beyond that, as a raw material it is a hard, grey metal with a high melting point. As witnessed by any classic car enthusiast it can be polished to an incredible shine and it has outstanding resistance to corrosion, which is why it is used as a protective and decorative coating for a huge variety of metal products. Its anti-corrosion characteristics are due to its ability to prevent the diffusion of oxygen into coated surfaces: swords and bolts coated in chromium, which date back 2,000 years, have been found without any signs of rust!

The most common form of chromium metal exists as an alloy in stainless steel, where it is used to increase hardness and as a protective and decorative finish, in this case it is applied as a very thin coating of as little as 0.0006cm. To distinguish it from engineering forms of chrome plating, decorative chrome plating is often used as a topcoat for bright nickel and offers that bright, shiny mirror-like finish. The product must be thoroughly cleaned and buffed in order to create a smooth, even surface. It is then electrically charged and immersed into the chromium solution, which is also charged. The charges cause an attraction between the surface of the component and the solution, which produces an even layer of chromium over the entire surface of the object.

Image: Chrome-plated mixer, Ufficio Progetti, Euromobil e R. Gobbo.

+	–
–Extremely hard –Corrosion resistant –Low cost –High-shine decorative finish	–Some plating processes produce toxins

Production
The most widespread use of chrome is in plating. Chrome plating involves electrically charging the component to be plated in a bath of chromium solution to make the coating stick to the substrate in a process called electroplating. There are typically two types of chrome coatings, the most common being the thin, decorative bright chrome that can be used on a wide range of equipment. The other form of plating is hard chromium plating, which is much thicker and is often used on industrial equipment to reduce friction and wear. Because it is such thin coating – 0.3 micron – it reproduces the surface it is on in every detail and flaw.

Sustainability issues
Hexavalent chromium is carcinogenic and extremely toxic in every way, which is why typical modern plating methods use trivalent plating.

Cost
£0.36 ($0.56) per kg.

Key features

- Very hard
- Capable of good surface finish
- Excellent corrosion resistance
- Electrically conductive

Sources
Widely available.

Typical applications
Decorative chrome plating has a history of use in a large number of components for cars, including door handles, bumpers and just about anything else that could be plated. It is also used on bicycles, furniture and door handles. It is alloyed with vanadium steel to produce tools such as spanners and alloyed with nickel for electrodes in spark plugs. However, today, many producers avoid using it due to toxins associated with its production in the plating process.

Derivatives
Chromium is commonly alloyed with the following metals:
–Chromium stainless steel
–Chromium copper
–Chromium molybdenum
–Chromium steel
–Chromium vanadium

Pewter

If the word traditional were a material it might be pewter. I am not sure why, but to me pewter is associated with being a medieval English material. Indeed, it is difficult to find any uses of pewter in contemporary design; unlike other metals it has associations that are more historical than modern. Visit any of the pewter industry websites and they are all steeped in the traditional values of craftsmanship. For example, pewter has a strong association with tankards and other products of antiquity, possibly due to the fact it has been used since at least Egyptian times.

In terms of its technical attributes, pewter's most distinguishing feature is its malleability, which comes from the high proportion – at least 85 per cent – of tin, with the remainder being a mixture of copper, antimony and a very small touch of bismuth; the copper and antimony add hardness to the otherwise soft tin. The Romans made pewter with approximately 70 per cent tin and 30 per cent lead; however, the proportion of tin varies greatly according to geographical and historical types. Fine pewter, for example, contains up to 95 per cent tin.

Miranda Watkins is one of the few contemporary designers using pewter in her work, and she has produced a range of tableware that finally moves pewter away from its connections with traditional products like the tankard.

Image: Groove bowl by Miranda Watkins

+	–
–Malleable –Doesn't tarnish –Achieves a high polish –Recyclable	–Can suffer from negative associations concerning past production processes

Production
According to the Worshipful Company of Pewterers, Pewter can be formed by the gravity method, cast in moulds of bell metal, steel or sand, cast with centrifugal casting or cast using rubber or silicone moulds. Its malleability also means that sheets of pewter can be cold-formed, rolled, spun on a lathe, pressed and hand formed. After production, pewter parts can be hardened by annealing, quenching and tempering.

Sustainability issues
Clearly, such ingredients as lead and antimony are serious issues in modern pewter and are no longer used. Pewter is recyclable.

Typical applications
Dishes, old-fashioned tankards and ornaments and, in particular, church ornaments occupy the largest areas of application for pewter.

Sources
Although China is the world's largest producer of tin, the UK's pewter industry has its strongest presence in Sheffield.

Key features
- Very malleable
- Achieves a high polish
- Non-toxic
- Does not tarnish
- Recyclable
- Relatively low melting point 250ºC (482ºF)

Cost
£30 ($20) per kg.

Aluminium *(Al)*

When aluminium alloys were first commercialized at the end of the nineteenth century they were a new and aspirational material. Used for applications such as cutlery and dinnerware, aluminium was seen as having greater status even than gold and was around twice the cost. In the 1950s aluminium went through another period of promotion, when its light weight and strength were applied to buildings and iconic vehicles such as the Airstream caravan. Like plastic, which has followed a similarly progressive series of interpretations and associations, aluminium still maintains its value as a material but with embedded aspirational values and, together with magnesium and titanium, is a part of the trio of lightweight metals. It's lightweight qualities were exploited in its use as the material for the 2012 Olympic torches.

In little over a century, this relatively new addition to the family of metals has become one of the world's most widely used metals, second only to steel. With its winning combination of strength, low weight and resistance to corrosion, aluminium has become the optimum metal for all kinds of transportation applications, including ocean liners, aircrafts and even spaceships. When ground into a powder form, aluminium is one of the few metals that retains a shiny appearance, which is why it is commonly found in paints and plastics, where it is used to produce a metallic effect. Aluminium is 100 per cent recyclable, and nearly three-quarters of all aluminium ever made remains in use today!

Image: Olympic Torch, Barber Osgerby

+	–
–Easy to processes –Versatile –Good strength-to-weight ratio –Corrosion resistant –Recyclable	–Extremely energy intensive to produce

Production
Aluminium can just as easily be formed for one-off production as it can for batch and mass production. Processing methods include extrusion, various forms of casting, machining and impact extrusion.

Sustainability issues
Producing aluminium is very energy intensive to process and as a result is extensively recycled due to the low energy needed to recycle it in comparison to extracting it from its ore. Recycling provides an energy saving of 95% over the use of the primary metal. The low weight and corrosion resilience of aluminium provides savings in weight and also in extending product life.

Sources
Bauxite, the ore from which aluminium is extracted, occurs mainly in tropical and sub-tropical areas – Africa, West Indies, South America and Australia – with some deposits in Europe.

Key features
- Good strength-to-weight ratio
- Low cost
- Versatile processing
- Non magnetic
- Achieves a high polish
- Excellent corrosion resistance
- Good machinability
- Melts at 660°C (1220°F)
- Recyclable

Derivatives
–Metpreg (aluminium with glass fibres)
–Nambe in the US produce various proprietary grades of aluminium in their range of designed products
–Duralumin (copper and aluminium alloy)
–Magnalium (aluminium and magnesium)
–Silumin (aluminium and silicon)
–Zamak (zinc, aluminium, magnesium and copper)

Typical applications
With a material that is so prolific it is impossible to describe its ‘typical’ applications because there are so many. They range from the ultra-precise, machined mid-section wings of the biggest commercial airliner in the world, the Airbus A380, down to a ring-pull on a fizzy drinks can.

Cost
£1.28 ($2) per kg.

Magnesium Alloys *(Mg)*

From our earliest primitive tools to the first attempts to fly we have searched to find lightweight, strong materials. Combine this with the increase in the number of people living in cities, commuting, transportation, increasingly nomadic lifestyles and a generation of products that more than ever require investment in reducing weight, and we have a situation where weight, or the lack of it, has a value. As the lightest commonly used metal – it is a quarter of the weight of steel and two thirds of that of aluminium – magnesium alloys clearly have a role to play in modern life.

First produced by British chemist Sir Humphry Davy in 1808, magnesium is an element with some extreme properties. It is very light, but it is also highly flammable and easy to ignite when powdered or cut into small strips. It is for this reason that magnesium makes an ideal fire-starter for camping and survival kits, where simply the sparks from a flint can be used to ignite it.

This flammability is also demonstrated by its use in early flash photography. Its main drawbacks, from a design perspective are that it develops a tarnished surface when exposed to air, giving it a utilitarian grey colour, and it has limited corrosion resistance, so much so that even fruit juice or carbonated water will stain magnesium alloys.

Image: Canon EOS 1D Mark IV magnesium alloy body

+	–
–Extremely lightweight	–Corrodes easily
–Widely available	–Poor surface finish
–Recyclable	–Hard to cold work
	–Highly flammable

Production
Like zinc, magnesium is one of the easiest metals to form into complex shapes that might otherwise be made in plastic. It can be processed by extrusion and various forms of casting, including investment casting and die-casting. When casting, sharp corners should be avoided as magnesium can be sensitive to stress concentration. Cold forming tends not be effective due to magnesium's tendency to work harden, which means that it gets harder the more it is bent. It can also be welded using a number of techniques. The surface can be enhanced through anodizing.

Sustainability issues
Using lightweight materials such as magnesium alloys in products significantly reduces energy consumption and transportation costs.

Sources
Magnesium is one of the most abundant metals in the earth with enough magnesium to make a planet of the same mass as Mars with leftovers. After sodium, it is the most abundant element in the sea.

Derivatives
Magnesium is generally alloyed with aluminium.

Cost
£2.55 ($4) per kg.

Typical applications
Some traditional pencil sharpeners were made from magnesium, other applications include chassis for consumer electronics, which exploit its light weight. It is also used for luggage frames and components such as foot pedals for bicycles. In addition to the uses of magnesium alloys, magnesium is a constituent of our bodies and magnesium oxide is used as a bleaching agent.

Key features
- Extremely lightweight
- Hard to cold work compared to aluminium
- Poor corrosion resistance
- Highly flammable—small pieces of pure magnesium burn easily
- Low electrical conductivity
- Poor surface finish
- Relatively low melting temperature: 650ºC (1202ºF)
- Recyclable

Tungsten *(W, aka Wolfram)*

Like titanium, tungsten has come to embody the idea of advanced properties that helps drive stories for designers. However, unlike titanium, which has the highest strength-to-weight ratio of any metal, tungsten is a superheavy metal. Tungsten suggests technology, hardness and, in certain applications, a sense of being premium quality, such as in these darts. Derived from the Swedish words 'tung' and 'sten' meaning heavy stone, its applications in design are fairly limited, but due to its significant properties it deserves to be mentioned in this book.

Its main attributes, beyond its heaviness, are an outstanding hardness and temperature resistance; it has the highest temperature resistance of all metals. Hardness is not the same as toughness, which is a term used for metals and describes the ability of a material to absorb impact energy without breaking; hardness is the ability of material to resist indentation, which means it resists scratching, wear and abrasion and is difficult to machine. Tungsten has one of the highest melting points of all metals and at elevated temperatures is also at its highest strength. Tungsten carbide is one of the most well known forms of tungsten and, as with all the carbide family of metals, has the highest melting point of all engineering materials. An interesting application of the material is its use in football boots in the form of a powder to shift weight towards the impact point, to help ensure the most effective control of the ball.

Image: Tungsten darts by TGV Design

+	–
–Very hard and dense –Corrosion resistant –High temperature resistance –Recyclable	–Hard to cast or machine

Production
Because tungsten has one of the highest ductile-to-brittle transition temperatures, its formability at room temperature is low. Its high heat resistance also makes it hard to cast, instead components are usually sintered from powder. It is available in various semi-finished states such as bars, tubes, wire, plate and sheets, from which it can be machined.

Sustainability issues
There are no major environmental concerns; however, tungsten powder has been known to have mild affects on animals and some reports suggest that it could be an 'emerging contaminant'. It can be recycled and 30% of tungsten production is based on recycled content.

Derivatives
–Tungsten steel
–Tungsten carbide
–Tungsten chromium
–Tungsten bronze
–Cobalt tungsten
–Copper tungsten
–Silver tungsten

Key features
• Very high density
• Very hard
• High corrosion resistance
• Low electrical conductivity
• Low toxicity
• Extremely high melting point: 3410°C (6192°F)
• Recyclable

Cost
£70 ($110) per kg.

Sources
Tungsten is not found freely in nature. The principal ores of tungsten are wolframite (an iron manganese tungstate). World tungsten mining and supply is dominated by China, which produces more than half of the world's output. Global production in 2011 was 72,000 tonnes with global reserves at 3,100,000 tonnes.

Typical applications
As one of the 'hard metals' its primary use is in heavy industry. In the shaping and cutting of other materials, particularly tool steels, it completely transformed the tooling industry. Apart from in darts, where its weight is used to stabilize its trajectory, tungsten is well known as the metal inside incandescent lightbulbs. Along with aluminium, cobalt, copper and zinc, tungsten is used in the nib of the common ballpoint pen. Less common applications include very hard and scratch-resistant tungsten and tungsten carbide jewellery, fishing weights, and bullets; vapour-deposited tungsten oxide layers are used in self-darkening windowpanes. It is also used in high-temperature applications such as welding anvils, and used to make the thin wire for the heaters in the back windows of cars.

Tin *(Sn)*

Tin is one of those materials that like paper ('paper-thin'), has entered common language to become an adjective, think of a 'tinny' sound. Partly as a result of this, it's not a material with associations of high value. Apart from its low perceived value, it also lacks any of the strong associations of other metals, such as aluminium, with its contemporary design applications or copper, with its associations of traditional kitchens.

Apart from being the main constituent of pewter, tin is also used prolifically within the packaging industry. If you come across a metal box, then the chances are that it is made from tinplate – steel coated on both sides with tin – a form of tin that equips it with good corrosion resistance. In its uncoated form, it can often be confused with aluminium due to its anaemic white, lustrous colour and surface finish. Aside from packaging, which accounts for about 90 per cent of its production, tinplate, which compared to other metals is relatively soft, is also familiar as the sheet metal from which simple toys are fabricated.

The history of tin dates back to the fourteenth century when it was the basis of a large craft tradition that involved cutting and folding sheets of tinplate. Even today there is still The Worshipful Company of Tin Plate Workers in the UK. Perhaps one of the most interesting aspects of tin is that it makes a sound when it is bent. Known as 'tin cry', the sound comes from the crystals deforming.

Image: Bloom vase by Meirav Barzilay

+	–
–Wide range of uses –Versatile processing –Corrosion resistant –Low cost –Recyclable	–Can suffer from low perceived value

Production
Tin plate can be rolled, easily soldered, die pressed, punched, laser cut and will react well to most other processes associated with sheet metal work for either one-off or mass production. Also, due to its low melting point, tin can be cast using very basic and inexpensive techniques in addition to conventional mass production casting methods.

Sustainability issues
Tin is non-toxic and is widely recycled.

Key features
- Soft and very malleable
- Easily forms alloys with other metals
- Good resistance to corrosion, excluding mineral acids (sulphuric acid, hydrochloric and nitric-acid)
- Low melting point, 232˚C (449ºF)
- Recyclable

Cost
£13.80 ($20) per kg.

Derivatives
–Pewter typically contains over 85% tin
–Bronze
–Brass contains no more than 40%
–Fields Metal contains around 17% tin

Typical applications
Most tin is used for solder and tinplate. Together with lead, it has one of the lowest melting points of metals. Tinplate is one of the most popular materials from which clockwork toys are made. Other uses include old-style toothpaste tubes and plating for steel 'tin cans'. It is also used as the liquid onto which glass is floated to produce 'float glass'.

Sources
The largest producers of tin are China and Indonesia, followed by a number of South American countries including Peru and Brazil.

Titanium *(Ti)*

My five-year-old son has a neoprene wetsuit with the word 'titanium' pasted across the arm. Like so many materials with high-grade properties titanium, when it is applied to consumer facing products, fits into our modern day obsession with 'advanced materials', which sometimes goes just a little bit too far. The 'advanced' profile of titanium has grown since its commercial introduction in the 1950s due to its use in high-tech applications that exploit its incredibly high strength-to-weight ratio.

Discovered by the British chemist Reverend William Gregor in 1791, titanium is named after the Greek god Titan, 'the incarnation of natural strength'. It is the ninth most abundant element on earth and has the highest strength-to-weight ratio of any metal – titanium is as strong as most steels and less than half the weight. It has been found in meteorites and it is believed to be present in the sun as well, so it comes as no surprise that titanium has excellent resistance to corrosion, a quality that accounts for its use in the aerospace, automotive and marine industries. Titanium is one of the few metals that is allowed to be used inside the body, a group that includes stainless steel, titanium-aluminium alloy, platinum and cobalt-chromium alloy.

Nearly all of the titanium ore extracted is made into white pigment, which is used in a huge range of products from paper to toothpaste.

Image: Leica M9 Titanium

+	–
–Heaviest strength-to-weight ratio of all metals –Corrosion resistant –Biocompatible –Recyclable	–High production costs –Difficult to cold work –Energy intensive to produce

Production
As with most metals, titanium can be hot and cold formed on standard machines; however, due to its low ductility at room temperature it is difficult to work into tight corners in sheet form. Also due to its low elasticity, forming in titanium needs to be compensated for due to its tendency to spring back. Both these issues can be addressed by forming titanium at elevated temperatures. Although not easy, it can also be welded.

Sustainability issues
The main issue with extracting titanium is that, like most metals, it is energy intensive, which raises the cost. Although there is no major recycling stream it can be recycled. Estimates by the US Geological Survey put global production in 2011 at 6,700,000 tons, with current reserves at 690,000,000 tons.

Key features

- Exceptional strength-to-weight ratio
- High corrosion resistance
- Biocompatible
- Poor thermal conductivity
- Non-magnetic
- Ductile
- Low electrical conductor
- High temperature resistance, 1660ºC (3020ºF)
- Recyclable

Cost
£13.40-17.90 ($21-28) per kg. Although titanium is an abundant element, it is costly to process into a metal form.

Sources
South Africa and Australia are the two biggest producers.

Typical applications
Around 95% of titanium extracted goes into the production of titanium dioxide pigment, with less than the remaining 5% being used in metal form. It is used to replace joints in the human body, in aircraft bodies, in turbines, as casings for consumer electronics and in buildings (the Frank Gehry-designed MOMA building in Bilbao is covered with titanium). Titanium nitride coatings are often used to protect blades and retain sharp edges in various cutters, drill bits and shaving blades. In this application it is a gold colour, in contrast to its natural dark grey.

Derivatives
There are many grades of titanium based on various alloys and also four grades of pure titanium, below are some of the most widely used:
–Nitinol (nickel-titanium)
–Beta C (titanium, vanadium, chromium, other metals)
–Medical-grade titanium (titanium, aluminium, vanadium)

Neodymium *(Nd)*

Neodymium is a soft, silvery metal that tarnishes easily, but it is what it does that is important, not how it looks. According to some, this element is more valuable than gold. Until relatively recently neodymium was just another one of the 16 rare earth elements (REEs) on the periodic table. However, this group of elements has been growing rapidly to the point that, according to a British Geological Survey in 2011, the REEs are the fifth most at-risk group of elements. Neodymium is one of the many materials that is driving the future of our products because of what it contributes to a vast range of industries.

This boom in the use of REEs is born from a succession of devices, mainly centred around renewable energy, where they are used for making highly efficient motors and other new technologies including smart phones. One of the most significant applications areas is in magnets, with neodymium, along with cerium, one of the most popular REEs, accounting for 30 per cent of the magnets used. In this field, neodymium is often alloyed to create super-strong magnets known as rare earth magnets. Magnets may not initially strike you as a major market but a succession of devices, including smart phones and X-ray machines, rely on their specific properties. It is for this reason that a huge amount of research is being carried out to try and find synthetic alternatives to what is the world's most powerful magnet and could be one of the most significant materials in the future.

Image: Neodymium magnets

+	–
–Source of renewable energy –Can reduce glare in glass –Growing range of applications	–Limited availability –Mining causes significant environmental impact

Production
Neodymium is generally bought as magnets, which are made by a sintered or bonded magnet process, for a range of uses.

Typical applications
Each Prius car uses around 1 kg (2½ lb) of neodymium in its electric motor. Another area of application is in wind turbines in the form of magnets. Neodymium has the ability to reduce glare in glass and is used in car windows for lower reflectivity. It is also used in glass for low-energy lightbulbs, and its spectral qualities, when used in glass, enhance the colour of TV screens. In mobile phones it is used to create the vibrate function and magnets for earphones. One of the derivatives of neodymium is a form of glass (also known as Alexandrite glass), which changes colour according to different lighting conditions. The glass appears lilac in natural sunlight or yellow artificial light, and blue in fluorescent and white light.

Sustainability issues
Over-mining is resulting in short supply of these rare elements. Also, according to some reports, the mining process used to extract neodymium can lead to radioactive waste leaks.

Sources
Neodymium has become a strategic material: China has the monopoly on global production with 97% of the world's supplies coming from China, largely from a single mine in Inner Mongolia. Currently, it has restrictions on its exports, which is causing a political situation with the rest of the industrial world and forcing new man-made neodymium to be developed.

Cost
£51 ($80) per kg.

Key features
- Super magnetism at a low weight
- Loses its magnetism at high temperatures
- Can lower reflection in glass

Derivatives
Neodymium glass.

Nickel *(Ni)*

Nickel is the sixth most abundant element on Earth, with one of its biggest uses being in bringing ductility and corrosion resistance to stainless steel. As such, it is more appropriate to discuss nickel as an ingredient in many alloys rather than as a stand-alone metal.

Nickel is a ductile, silvery white metal with a good resistance to corrosion. However, when it is alloyed to other metal ingredients, like steel, chromium and titanium, its properties are enhanced to produce what are known as superalloys. One major area of application is for aircraft engines, where nickel-based superalloys are used in the hottest parts of aircraft engines, where temperatures exceed 16000ºC (28832ºF). Alloyed with chromium in the proportion of 18 per cent chromium and 10 per cent nickel it is used to produce 18/10 stainless steel, the mark that can often be found on stainless steel cutlery.

Nickel is also alloyed with titanium (called nitinol) in what are known as shape-memory alloys, which have outstanding uncrushable springiness and are used in wired bras and bendable spectacle frames. Nitinol has 20 times the elastic strain of steel. Nitinol also has one of the most interesting properties in the rapidly emerging field of smart materials, where they exhibit a shape-memory effect that allows for specific shapes to be 'programmed' into a metal, often wire, which once distorted will revert back to its former shape if heated.

Image: Shape-memory paperclips

+	–
–Key component of super alloys –Good hardness –Corrosion resistant –Super-elastic when alloyed with titanium	–Can cause skin irritation

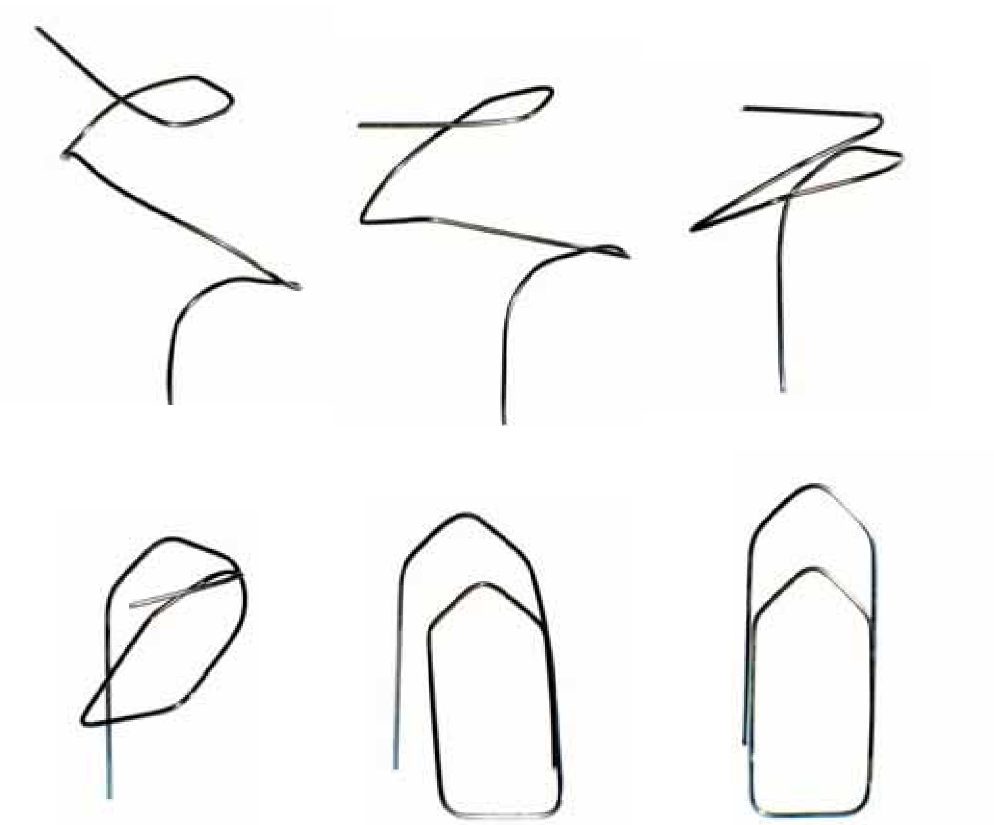
Production
As an alloy, its processing is dependent on its alloy partner. But generally, most metal processing forms are applicable: stamping, forging or rolling, cold drawn.

Sustainability issues
As well as the applications of nickel alloys mentioned above, nickel is also used in pigments for paint, pottery, glass and plastics. Although some people suffer sensitivity and allergic reactions to nickel, its only major risk to health is in certain areas of its processing, where significant exposure could lead to health risks.

Key features
- When alloyed with titanium it has super-elasticity and shape-memory properties
- Good corrosion resistance
- Good hardness
- Can cause skin allergy
- High melting point –1455ºC (2651ºF)

Sources
In 2009, Russia was the largest producer of nickel with about one-fifth of the world share, closely followed by Brazil, Canada and Australia.

Cost
£22 ($14) per kg.



Derivatives
- –Cupronickel (copper-nickel)
- –Nitinol (nickel-titanium)
- –Nichrome (nickel, chrome, iron)
- –Stainless steel (chromium-nickel)
- –Hastelloy
- –Nimonic
- –Inconel

Typical applications
The main uses for nickel are as an alloying element, examples of which include springs, nickel-cadmium batteries, heating wires and super-elastic alloys. Super-elastic alloys are more common than you might think and are used in everyday applications, which apart from bras and spectacle frames include orthodontics and jewellery. It is also widely used for electroplating and as a replacement for steel in turbine blades in jet engines, where it performs well at extreme temperatures.

Zinc *(Zn)*

Zinc lacks the personality and strong associations of many other metals, for example the premium, lightweight associations of magnesium or the luxury associated with silver. Visually it's not that striking either, but it is still a very important material, not just in its own right but also as a partner for other metals.

Zinc alloys can be characterized as the metals most likely to be used as alternatives to plastics for making complex components. Zinc has a silvery blue-grey colour and is the third most used non-ferrous metal after aluminium and copper. According to the US Bureau of Mines, the average person will use 331 kg (730 lb) of zinc in his or her lifetime.

Its low melting point is one of the key reasons zinc is such an ideal material for casting. Zinc castings are everywhere in products that take advantage of the metal's suitability for making detailed and complex metal parts, for example, under the skin of chromed door handles, bathroom taps and corkscrews. And apart from its use for casting, its high corrosion resistance means that one of its other primary areas of use is as a partner to steel for galvanizing. Apart from steel, another major use of zinc is as an alloy to copper for forming brass.

Image: Stanley knife casing made from zinc

Production
One of the main areas for processing zinc alloys is in pressure die-casting. Another new area of production that zinc can be applied to is spin casting, a method of casting small components for quick evaluation before full-scale production. In terms of applying decorative surfaces, it can be electroplated, painted and anodized.

Sustainability issues
According to the US Geological Survey in 2011, zinc production was at around 12,000 tons per year with current reserves at 250,000 tons. In the same year in the US around 53% of the zinc used was from recovered sources. As a material with a low melting temperature it could be argued that it has less embodied energy than high-melting-point metals.

+	–
–Low cost –Ideal for casting –Corrosion resistant –Recyclable	–Relatively brittle –Not attractive but takes decorative finishes well

Typical applications
Apart from its use in galvanizing as protection against corrosion, zinc alloy castings have been used as an alloy for producing bronze. Zinc alloys are often difficult to find in their raw state as they are often coated, for example, the ordinary kitchen corkscrew is often made from a zinc alloy, which is nickel-plated. But its corrosion resistance is not just used for steel; it is also an indispensable element for our bodies, which supports our immune system.

Sources
Zinc is the twenty-fourth most common element on the Earth. There are zinc mines throughout the world, with the main mining areas being China, Australia and Peru. China produced 29% of the global zinc output in 2010.

Key features
- High corrosion resistance
- Alternative to plastics in forming complex parts
- Capable of good surface finish
- Low cost
- Relatively brittle
- Good hardness
- Alloys well with other metals
- Hygienic
- Low melting point
- Recyclable

Cost
£1.15 ($1.8) per kg.

Carbon Fibre

Carbon exists in both crystalline and amorphous forms, which goes some way to explain how, from a single substance, a vast array of materials ranging from graphite to carbon fibre with opposing properties can be arrived at. Amorphous materials have no definite shape, they break to give curved or irregular faces, and they also soften and will melt over a specific temperature range. Crystalline materials consist of individual crystals, and are arranged in a well-defined shape.

Although it originates from the same element as diamond, carbon fibre is one of the new man-made, high-tech materials that has come to be associated with premium, high-end luxury. Consisting of shiny black filaments of fibres drawn from approximately 90 per cent carbon it is renowned as a high-performance material with aspirational qualities. These associations are partly based on beautiful pattern of the fibres and also because of its high tensile strength. Although in products like high-end pens, the tensile strength is not of huge benefit, it is worth noting that in comparison to a human hair, which has a tensile strength of 380MPa, carbon fibres – at 4137 MPa – have one of the highest tensile strengths of any widely used material. This is partly because of its atomic structure. Unlike the layered, chicken-wire structure of graphite – another form of carbon – carbon fibres consist of ribbons of carbon atoms aligned parallel to the axis of the fibres, giving it its supreme strength.

Image: Terence Woodgate table

+	–
–Relatively lightweight –High tensile strength –Withstands high temperatures	–Limited recycling options

Production
Carbon fibres are one the most widely used performance fibres for advanced composites. They can be woven into textiles and used with epoxy or polyester resins to reinforce plastics in processes such as filament winding, pultrusion and autoclave moulding to give a higher strength-to-weight ratio than metals.

Sustainability issues
The high strength-to-weight ratio of carbon fibre composites often means a weight reduction in many applications, especially aviation and transport, which can result in fuel savings. The main eco issue with any composite material is around recycling. Although there are more and more companies who are able to separate the raw materials, composites are notoriously difficult to reuse. However, there are a limited number of companies who can recycle carbon fibres.

Derivatives
Textreme®

Typical applications
Applications range from the purely banal, such as toilet seats, to car chassis in Formula One. Other uses include 'exclusive' pens, tennis requests, fishing rods and industrial applications for aircraft and civil aviation.

Cost
£22.60 ($35) per kg.

Key features
- High strength-to-weight ratio
- Four times as a strong as high-tensile steel
- Resistant to compression
- Chemically inert
- Resistant to chemicals
- Low friction
- Non-toxic
- Good stiffness
- Can withstand high temperatures

Sources
Widely available.

Graphite

How can a material have both high-tech applications, such as for sports goods, and yet also have the very slippery attribute as the basis of the lead in a pencil? A common misconception is that pencil lead is lead; it is in fact graphite. Graphite, carbon fibre and diamond are all allotropes of carbon – different atomic structures based on the same element.

Both graphite and diamond demonstrate, on an atomic level, the importance of material properties and functionality when structure is altered. The ultimate hardness of diamond is based on a triangular tetrahedral structure, while graphite has a layered structure –imagine layers of chicken wire on top of one another. It is this layering that creates the slipperiness of graphite, three million layers of which would be 1 mm (1/16 in) thick.

This silvery black, slippery carbon allotrope with a metallic sheen that defines the visual identity of graphite, is marked by three main forms: flake graphite, made up of crystal structures; amorphous graphite, which is soft and non-crystalline; and synthetic graphite, which constitute the largest commercially used form. One of the most interesting characteristics of graphite is its excellent conductive properties; something that can be demonstrated by drawing a pencil line across two electrical contacts. This is the idea behind Paul Cocksedge's graphite lamp, shown here. A graphite pencil trail completes the circuit and conducts electricity to the lamp.

Image: Paul Cocksedge graphite lamp

+	–
–Good electrical conductivity –High strength-to-weight ratio –Good chemical resistance –Good resistance to thermal shock	–Environmental concerns –Prone to flaking and breaking apart

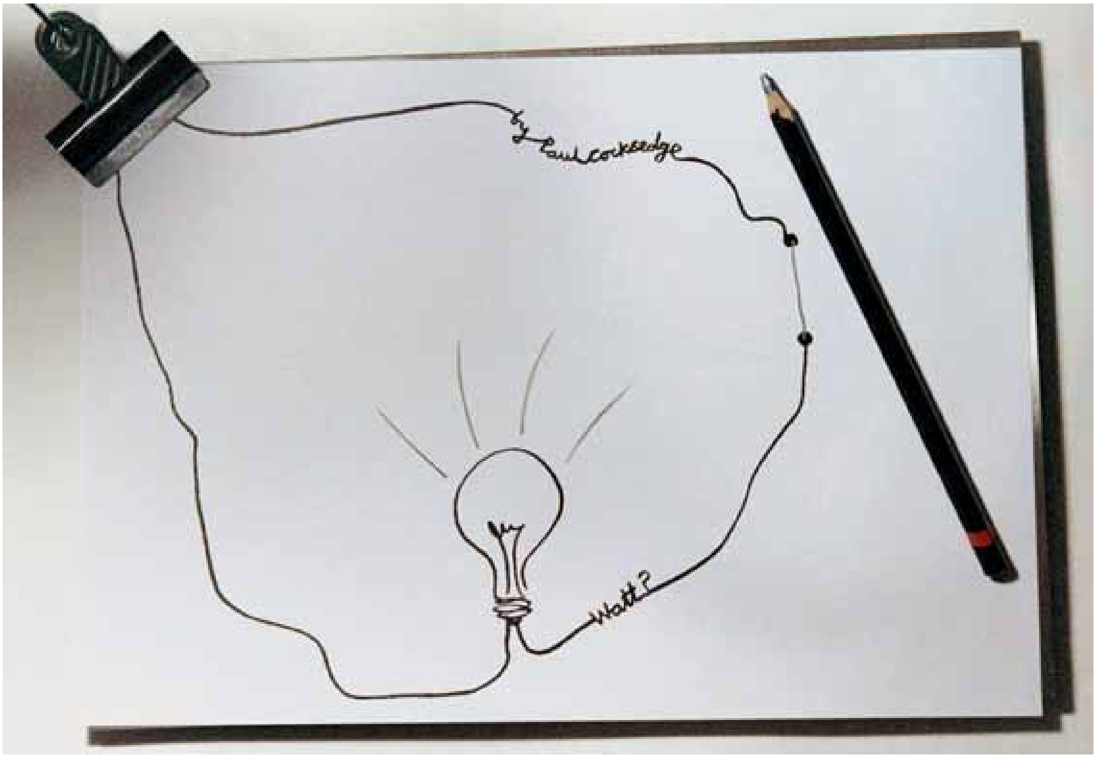
Production
Graphite can be moulded, sintered, used as a lubricant in its powdered form, added to metals and plastics to make them stronger

Sustainability issues
If not responsibly maintained, the environmental impacts of graphite mills can include air pollution and soil contamination from powder spillages leading to heavy metals contaminations of soil. Graphite can be recycled, and it is one of the materials being explored for use in alternative energy applications.

Key features
- High strength-to-weight ratio
- Resistant to compression
- Chemically inert
- High resistance to chemicals
- Low friction and self-lubricating
- Non-toxic
- Good stiffness and energy absorption
- Good machinability
- Good electrical conductivity
- Flaky and breaks apart
- High resistance to thermal shock
- Temperature resistance is 3000ºC (5400ºF)

Sources
China is by far the largest producer of graphite. Other producing countries include Ukraine, Brazil, Russia, Canada, India, Zimbabwe, Norway, Mozambique Sri Lanka, Germany and Madagascar.

Typical applications
On a basic level graphite is used in everyday objects, such as pencils, where its soft, slippery qualities are put to good use to create what is essentially a graphite trail on a piece of paper. Its plate-like structure also makes it a good lubricant, especially at high temperatures. But on an advanced level it is a key player in advanced performance sports equipment, where it is used for golf clubs and tennis racquets, and it has an excellent strength-to-weight ratio and high-energy absorption. Graphite is also used in lithium-ion batteries, an increasingly important power source for e-vehicles and other areas of clean-tech.



Cost
This varies depending on grade, but generally ranges from £0.32-2.60 ($0.50-4) per kg.

Derivatives
–Graphene: single layers of graphite are graphene, the material that won Andre Geim and Konstantin Novoselov from Manchester University the Nobel Prize for Physics in 2010.
–Pyrolytic graphite, a material that will float over strong magnets.

Iron *(Fe)*

One of the most abundant elements on the planet – and in the universe – and one of the oldest in production, iron is also still one of the most widely used materials. Its defining moment in history occurred when human evolution was still characterized by our application of materials, when iron marked the point in history that, through the forming of this ductile material, we were able to develop new tools to transform the world. However, beyond its use as the basis for steel, there are a limited number of applications today where a designer would specify iron in its raw form.

In its raw form, iron can be processed as castings or as wrought iron. Its properties vary depending on the grade but wrought iron – a term to describe the process of 'working' or forming the metal – is generally tougher and less brittle than cast iron. However, it does come in a variety of forms, such as pig iron, the main form of cast iron. Others include grey iron, ductile iron, white iron, compacted graphic iron, malleable iron and high alloy irons. One key additive that is used to affect the properties of iron is carbon, which is used to make steel. As a rule, the higher the carbon content the more brittle it becomes.

Culturally, this lustrous grey metal is perceived as being a crude, unrefined material. Not used for beauty but to deliver performance and to exploit its substantial weight. Its rough grey surface establishes it as a material for industry.

Image: David Mellor's Cast Iron Candlesticks

+	–
–Versatile processing	–Mining causes significant environmental impact
–Low cost	–Relatively brittle
–Very strong	–Poor corrosion resistance
–Recyclable	

Production
The relatively low melting temperature of iron makes it suitable for a range of production volumes, from small one-off pieces made of wrought iron to larger production runs that use casting methods to produce parts. As a relatively brittle material, one of the main considerations during production is to avoid thin profiles or sharp corners, which would make the iron prone to breaking.

Sustainability issues
Iron is one of the most abundant of Earth's elements. However, the process of extracting the ore from the Earth and the use of heat to transform it are the main considerations in relation to environmental impact.

Derivatives
–Anthracite iron (carbon)
–Cast iron (carbon)
–Pig iron (carbon)
–Wrought iron (carbon)

Sources
According to the US Geological Survey in 2011, world steel consumption was expected to be 1,398 million tonnes. China is responsible for almost half of the world's iron production, which in 2011 was 700,000,000 tonnes.

Key features
There are vast differences in the properties of iron depending on its form and how it is processed

- In its pure form it is very ductile, corrodes easily and is chemically reactive
- Good compression strength
- High stiffness
- Magnetic
- Low melting temperature: 1538˚C (2800ºF)
- Recyclable

Cost
Price is variable depending on type, but in general iron is the least expensive metal.

Typical applications
Cast iron was used in everything that drove the industrial revolution, such as bridges, construction (the Eiffel tower is made from wrought iron). factory machinery and transportation. Today, it's used for cooking pans and manhole covers and, as any child who remembers the fun science experiments will know, magnetic iron filings. Wrought iron dates back to much earlier times and was used by the Romans. Iron is an essential part of our bodies.

Molybdenum *(Mo)*

Molybdenum is a metal that is almost always part of an alloy and as such is not like many other metals. The primary reason for its inclusion here is its functional rather than aesthetic appeal. The most notable performance characteristic of molybdenum is that it has one of the highest melting points of all metals and, together with carbon, is one of the most effective hardening elements for steel alloys. Like tungsten, which it is often used to replace, it increases the hardness of steel, but a smaller amount is required to achieve the same hardness.

Molybdenum and vanadium are used in small amounts in steel to increase its tensile strength and toughness. It also increases the fatigue-resistance of steel, and this contributes to the performance of the Global® range of kitchen knives. These 'designer tools' borrow from the traditions of Japanese Samurai swords, where each knife is handcrafted to form a seamless construction. The molybdenum/vanadium stainless steel is ice-tempered to produce a hard, razor sharp blade that resists stains and corrosion.

For its application in the knives, it is important to understand its function. In stainless steels, corrosion resistance usually comes from the chromium content, which spontaneously forms a thin, protective inert film on the surface of the steel. Molybdenum enhances this film by making it stronger and helping it to reform quickly if it is damaged and increases the pitting and crevice corrosion resistance of stainless steels.

Image: Global® knife

+	–
–High tensile strength –Very high temperature resistance –Good stiffness –Food grade –Corrosion resistant	–Cannot be hardened by heat treatment –Comparatively expensive

Production
Molybdenum's main application areas are where it is used as an alloy. In its unalloyed state its softness allows it to be drawn into thin sheets and wire. Molybdenum and its alloys can be formed by all common metalworking practices, such as bending, punching, stamping, drawing and spinning but unlike other metals, it can't be hardened by heat treatment.
A process known as vapour deposition, or thermal spraying, can also be used to apply the metal as protective coating. It can also be formed using metal injection moulding, welded and brazed, but welding is normally used only for applications not subjected to great stress.

Sustainability issues
Estimates by the US Geological Survey in 2012 put known reserves of molybdenum at around 20 million tonnes. They also reported that 'molybdenum in the form of molybdenum metal or superalloys is recovered, but the amount is small. Although molybdenum is not recovered from scrap steel, recycling of steel alloys is significant, and some molybdenum content is re-utilized. The amount of molybdenum recycled as part of new and old steel and other scrap may be as much as 30% of the apparent supply of molybdenum.' Compared with other heavy metals it has low toxicity, a reason why it can be used in food processing equipment.

Cost
£57-76 ($90-120) per kg.

Key features
- High tensile strength up to high temperatures
- Good corrosion resistance
- High stiffness
- Ductile
- About 34% of electrical conductivity of copper
- High melting temperature of 2610°C (4753°F)

Derivatives
–Hyten steel containing nickel-chromium and molybdenum
–Duplex stainless steels

Sources
Most molybdenum is produced in the United States, with Norway, China, Chile, Mexico, and Peru also being producers. It is mined as a principal ore, but is also recovered as a by-product of copper and tungsten mining.

Typical applications
One of the most interesting uses of molybdenum is for steel plates in armoured tanks, but one of its main uses is to replace tungsten in high-speed steels. It can be alloyed with steel to improve hardness at high temps, for example, for steel cutting tools; however, by far the biggest application of molybdenum is in structural steel, where it has been used as cladding for skyscrapers.

Stainless Steel

When Apple introduced the first iPod, it was an audacious decision to use stainless steel for the back plate. Yes it's beautiful, but it's also a material that goes against expectations because it dents and scratches easily. However, the use of this 'real' material in place of plastic has changed the world's expectations of materials in consumer electronics.

Well before Apple redefined the perceived applications of stainless steel, its introduction – under patents taken out in 1914 – provided the opportunity for a new language for products and in new product territories. This 'non-rusting' powerfully strong steel changed the world from its origins in Sheffield in the UK, which became a global hub for the material.

Stainless steel is steel alloyed with chromium, nickel and other elements. It owes its 'stainless' properties to the chromium, which creates an invisible, tenacious and self-healing chromium oxide film on its surface, a surface that can be enhanced further by molybdenum. Stainless steel is often referred to by the mix of chromium and nickel: 18/10, for example, refers to steel that is 18 per cent chromium and 10 per cent nickel, the ingredient that gives it a silvery sheen. 18/0 is much less expensive than 18/10 and most cutlery sold today is made from this material. 18/10 gives greater protection against corrosion and has a softer shine: most contemporary patterns are made from this top-grade stainless steel. 18/0 and 18/10 are both fully dishwasher-safe.

Image: Super Star TK03 bowl by Tom Kovac for Alessi

+	–
–Versatile processing –Extremely tough –Finishes well –High temperature resistance –Recyclable	–High cost –Difficult to cold work

Sustainability issues
Recyclable.

Derivatives
The four major types of stainless steel:
Austenitic is most widely used type of stainless steel. It has a nickel content of at least 7%, which gives it ductility, a large scale of service temperatures, non-magnetic properties and good weldability. The range of applications includes housewares, containers, industrial piping and vessels, building structures and architectural facades.
Ferritic stainless steel has properties similar to mild steel but with better corrosion resistance. The most common of these steels contain 12% and 17% chromium, with 12% chromium steel used mostly in structural applications and the 17% in housewares, boilers and washing machines.
Ferritic-austenitic stainless steel has both ferritic and austenitic lattice structures, hence its common name, duplex stainless steel. This steel has some nickel content for a partially austenitic lattice structure. The duplex structure delivers both strength and ductility. Duplex steels are mostly used in the petrochemical, paper, pulp and shipbuilding industries.
Martensitic stainless steel contains between 11 and 13% chromium and is both strong and hard with moderate corrosion resistance. This steel is mostly used in turbine blades and in knives.

Production
Compared to other steels, stainless steel is fairly versatile in terms of processing – it can be folded, bent, forged, deep drawn and rolled. Standard grades are difficult to machine because of the hardness of the material, although specific grades are available that are much easier to machine. As a result of this versatility it is suited to production volumes ranging from one-off to mass production..

Sources
According to the US Geological Survey in 2011, world steel consumption was expected to be 1,398 million tonnes. China is responsible for almost half of the world's iron production, which in 2011 was 700,000,000 tonnes.

Cost
£3.20 ($5) per kg.

Key features
- Non-corrosive
- Excellent toughness
- Achieves a high polish
- Difficult to cold work due to hardness
- High temperature resistance
- High weight
- High cost
- Recyclable

Typical applications
Stainless steel is generally used in environments where there is the risk of corrosion and heat resistance: its properties have been applied to kitchen equipment, tableware, architectural applications, engine components, fasteners, and tools and dies in production. In buildings, possibly one of the most striking applications are the gleaming panels at the top of the Chrysler Building in Manhattan. It is also able to remove smells from the skin and so is formed into handheld pebbles for cleaning the hands.

Steel

Arguably, one of the most important materials in the world is steel, which strikes the balance between strength, easy forming and being very cheap. Steel is a material that evokes associations with heavy industry, but to really understand steel and its value to the world, one should think of it as a raw material from which a whole range of derivatives, with different nuances, can be formed.

Steel is obtained by alloying iron with small amounts of carbon. It is the inclusion of carbon in varying degrees and the way oxygen is allowed to escape during processing that determines the properties of the vast number of grades of steel that can be formed. These steel grades can be broadly split into two main groups: carbon steels and alloy steels. Within the branch of carbon steels there are further broad categories including mild steel, medium and high carbon steels. The lower the carbon content, the milder the steel but also the tougher; the higher the carbon, the harder the steel (i.e. stays shaped for longer) until you reach about 4 per cent carbon, at which point the metal becomes cast iron.

Cold working steel increases its strength and decreases ductility and, like aluminium, steels can be alloyed to increase their physical properties. These alloys include lead to increase machinability, cobalt, which increases hardness at high temperatures, and nickel, which increases toughness. Like aluminium, steel is classified by the use of four digits.

Image: Krenit bowl, Normann Copenhagen

+	–
–Very strong –Versatile processing –Low cost –Tough –Recyclable	–Poor corrosion resistance

Production
Annealing steel – heating it to make it softer – is one of the major ways of processing steel. Beyond this, it can be cast, machined, rolled, extruded, press-formed and many of the other forms of production associated with forming metals.

Sustainability issues
Steel requires more heat energy to form than plastics, it is widely available and it is recyclable, requiring comparatively low energy.

Sources
According to the US Geological Survey in 2011, world steel consumption was expected to be 1,398 million tonnes. China is responsible for almost half of the world's iron production, which in 2011 was 700,000,000 tonnes.

Cost
£0.40–0.60 ($0.63-0.84) per kg.

Key features
- Tough
- Comparatively low energy use to form
- Low cost
- High weight
- Corrodes
- Recyclable

Derivatives
–Steel is often alloyed with Tungsten, Manganese and Chromium
–Stainless steel (chromium, nickel)
–Silicon steel (silicon)
–Tool steel (tungsten or manganese)
–Bulat steel
–Chromoly (chromium, molybdenum)
–Crucible steel
–Damascus steel
–HSLA steel
–High speed steel
–Maraging steel
–Reynolds 531
–Wootz steel

Typical applications
Mild steel is used a lot in structural elements in building, for example I-beams and for reinforcing. Medium carbon steel is used in heavy industry for railway tracks. High carbon steels are used for various cutting tools such as chisels and drill bits and on a softer note for the strings in violins and piano wire.

Bone China

The inherent strength of a material informs the nature of the shapes that can be produced from it. Strength, one of the key physical characteristics of bone china, means that it can be formed into thin, delicate sections, conveying an exquisiteness that is associated with the refined image of fine ladies drinking tea. Interesting then, that this material is partly made from a by-product of the food industry, with 50 per cent of the ingredients being made of bone ash, (calcium phosphate), the remaining ingredients are 25 per cent Kaolin (china clay) and 25 per cent quartz.

An English potter developed bone china in the eighteenth century as a result of trying to replicate porcelain from China, where it had been used for over a thousand years. Although they are both hard, white and translucent, bone china and porcelain are different materials and so require different processing, for example, bone china fires at lower temperatures to porcelain. Belonging to the vitrified – containing glass – group of ceramics the china content gives the substance its hardness, which is why it is possible to make thin, fine sections and details. The fact it is a vitreous ceramic also helps with its resistance to moisture. The colour of bone china is white but is also distinct from porcelain in that it is a slightly creamier shade of white; however, both are translucent.

Image: Crushed Bowl by JDS Architects for Muuto Denmark

+	–
–Very strong and hard –Water resistant –Excellent chemical resistance –Can be formed in very thin sections	–Relatively high cost –Not recyclable –Energy intensive to produce

Production
The production of bone china follows similar methods to other ceramics, including slip casting, extrusion, jiggering and jollying and compression moulding. Due to its strength it is ideally suited to slip casting, which allows for thin wall sections.

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be remoulded. However, they can be crushed and used as fillers and gravel for various industrial applications. The main issue with ceramics is the intense heat that is used during firing, and often, when a ceramic needs glazing, this will involve a second firing process.

Derivatives
Cornish stone, also known as china stone. Less decomposed than china clay, containing a large amount of feldspar. Generally used as a flux and porcelain bodies.

Sources
Kaolin, one the major ingredients in bone china, is quarried in various places in the UK, one specifically being Cornwall. In France it is quarried in Limoges. In the UK, Stoke-on-Trent is the home of many ceramic products.

Cost
The cost of the raw materials, the higher tolerance needed in firing temperatures and the general care needed in production means that relative to other ceramics it is expensive.

Typical applications
This high-grade English pottery has its main use in tableware. China clay, however, is used for making various forms of porcelain; as an abrasive powder; as a refractory material; as an electrical insulator; as a pigment in paints; and as a filler for plastic mouldings to reduce moisture absorption. Vitreous china is also used to make sanitary-ware due to it its ability to resist moisture content.

Key features
- High strength means thin cross-sections
- Excellent hardness
- Less brittle than porcelain
- Good electrical resistance
- Whiter than porcelain
- Translucent
- Vitreous, making it resistant to water
- Excellent chemical resistance
- Non-porous
- Biscuit fired at around 1200ºC (2192ºF)

Porcelain

Porcelain is a well-bred material: capable of being fine and delicate and with a history that dates back to 600CE China. Its provenance is the reason it is often referred to as china or chinaware. It was not until the invention of bone china in England in the eighteenth century that it had any competition as a fine, hard, ghostly translucent white ceramic.

Porcelain is not just suitable for fine dinner services; its combined properties of hardness and good electrical insulation also make it ideal for more rugged applications. As a material for electrical insulation, porcelain has been used for spark plugs, lighting and power cable insulation; its use in these products went hand-in-hand with the discovery of electricity.

Electrical insulators for power cables and railways came to prominence because of the need to move electricity from one place to another. The multitudes of porcelain insulators that exist around the world come in an assortment of shapes and colours. These different shapes reflect the different power requirements for where they were to be placed. They also needed to be designed to accommodate varying degrees of insulation; others were designed to hold the line wire more efficiently. Some manufacturers even went as far as to patent their shapes.

Image: Rice bowls by Alexa Lixfield

+	–
–Very strong and hard –Excellent electrical and chemical resistance –Versatile processing –Can be formed into thin sections	–Not recyclable –Energy intensive to produce

Production
As with bone china (see page 202), the strength of the material means it can be formed into thin, crisp wall sections, which are suited to slip casting. Traditional methods of ceramic production also apply, such as turning, extrusion, jigger jollying and compression moulding. Railway insulators are still made by hand-turning the porcelain on a lathe.

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be re-moulded. However, they can be crushed and used as fillers and gravel for various industrial applications.
The main issue with ceramics is the intense heat that is used during firing, and often, when a ceramic needs glazing, this will involve a second firing process.

Cost
Porcelain is about half the cost of bone china, but more expensive than earthenware, stoneware and terracotta.

Typical applications
Porcelain is used in a range of products, including dental brackets and crowns, electrical insulators, tableware and decorative figurines. High-tension porcelain is used mainly for applications where high voltage is present but it is also used for the production of pestles and mortars. Porcelain enamel is used as a protective and decorative coating that is applied to high temperature metals. It is, of course, also used for porcelain tiles for interiors and exteriors.

Sources
Widely available in various parts of the world, but France and the UK are the largest producers of porcelain.

Derivatives
High-tension porcelain.

Key features
- High strength means thin cross-sections
- Excellent hardness
- Scratch resistant
- Vitreous, making it water resistant
- Translucent
- Excellent electrical resistance
- Excellent chemical resistance
- Non-porous

Earthenware

Earthenware ceramics are simply plain ceramics, unremarkable and lacking in any distinct personality, in fact, if you were to compare earthenware to food it might be as dull as brown rice without the seasoning. However, its contribution to the world is undeniable. For example, the chances are that the coffee cup sitting on your desk as you read this is earthenware, simply because it occupies the largest area of ceramic production due to its balance of useful characteristics, all available at the right price.

In comparison with porcelain, stoneware and bone china, earthenware contains less glass. As a result, this porous ceramic needs to be covered by a glaze in order to hold liquids. Unlike the vitreous and translucent porcelain or china, earthenware is also opaque. It is not as strong or as dense as bone china or porcelain and is prone to chipping but it does have the advantage of less distortion occurring in the lower firing temperatures and is therefore more stable during processing: another reason why it is so prevalent.

Image: Bowls, Ineke Hans for Royal VKB

Production
Unlike porcelain or bone china, which are perceived as being 'premium' materials, earthenware ceramics are more straightforward and easy to process. From high-volume mass production to one-offs they are approachable in terms of both production and cost criteria. As with other ceramics, earthenware can be extruded, slip cast, turned on a lathe and jigger jollied.

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be re-moulded. However, they can be crushed and used as fillers and gravel for various industrial applications. The main issue with ceramics is the intense heat that is used during firing, and often, when a ceramic needs glazing, this will involve a second firing process.

+	–
–Versatile processing –Low cost –Stable during processing, unlike some ceramics	–Prone to chipping –Not recyclable –Energy intensive to produce

Sources
Widely available.

Key features
- Versatile processing
- Straightforward to form
- Low cost
- More prone to chipping than china or porcelain
- Not as dense or as strong as stoneware
- Fired below 1200°C (2192°F) is classed as earthenware

Cost
A very low-cost ceramic.

Typical applications
It is difficult to narrow down where earthenware is used. It is to ceramics what pine once was to kitchen furniture; used in all product areas, from large sanitary ware to mugs and plates.

Stoneware

The first examples of stoneware date back to China's Shang Dynasty, two millennia BCE. The name stoneware does a superb job of suggesting the qualities of this gritty ceramic. Like porcelain and bone china, stoneware is non-porous, hard and water resistant. However, unlike earthenware, stoneware – like bone china and porcelain – is a vitreous ceramic, which means it contains glass; this results in a product that is suitable for holding liquids without the need for glazing, although products such as tableware and decorative objects are often glazed to give an attractive finish. Stoneware is more chip-resistant than earthenware, and more opaque than porcelain. It is usually grey or brown in colour due to impurities in the clay. The British tableware manufacturer Wedgwood uses stoneware in a specific form, known as Jasperware, which is marked out by its distinctive, rough, pale blue, textured finish.

Different types of stoneware are available, from traditional stoneware – which is dense and inexpensive, made from secondary clays – to chemical stoneware, which is made from purer raw material and can be used to create large vessels for storing highly corrosive liquids such as acid.

Image: Work table lamp by Dick van Hoff

Production
As with bone china, the strength of stoneware means it can be formed into thin wall sections, which are suited to slip casting. Traditional methods of ceramic production also apply, such as turning, extrusion, jigger jollying and compression moulding.

+	–
–Very hard –Water resistant –Low cost –Good electrical resistance –Good wear resistance	–Not recyclable –Energy intensive to produce

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be re-moulded. However, they can be crushed and used as fillers and gravel for various industrial applications. The main issue with ceramics is the intense heat that is used during firing, and often, when a ceramic needs glazing, this will involve a second firing process.

Sources
Widely available.

Key features
- Stone-like quality
- Not easy to work as a clay
- More stable in the firing than clay
- Vitreous, making it water resistant
- Good abrasion and wear resistance
- Good electrical resistance
- Non-porous
- Fires at 1183°C (2161°F)

Cost
Varies according to grade, but generally inexpensive.

Typical applications
The hard and vitrified nature of stoneware means it has applications as water-resistant tableware without the need for glazing. As a highly vitrified ceramic it is also widely used in chemical and electrical products due to its good electrical resistance and low water permeability.

Terracotta

Terracotta has been used since the earliest times – for example, the terracotta army from China dates back to 210–209 BCE. One of the simplest expressions of earthenware ceramics, terracotta is the material used in flowerpots but behind its suntanned, digestive biscuit texture lays an interesting scientific phenomenon that actually contributes a functionality to the product that most people are unaware of.

Translated from the Italian for baked earth, terracotta is unglazed, semi-fired clay with a distinctive dry, creamy red biscuity texture, which is obtained through washing the clay and mixing in only the finest particles of sand. Although the red variety is the most common, it is also found in yellow and even a milky white, depending on where it is mined.

In relation to its use in flowerpots, the porosity of terracotta gives it one of its distinguishing and unique features. It is because of its pores that an interesting osmotic effect is produced, allowing for natural evaporation of water through its surface. It's this property, combined with its low cost, that makes terracotta such a good material for flowerpots. Plants drain more easily and dry earth can be kept wet through this osmotic process. The effect has also been used in traditional water containers to keep drinking water cool in hot climates, an application which has been interpreted in a contemporary design of a bottle by Royal VKB. This application also highlights the novel combination of traditional terracotta with a modern silicone rubber foot.

Image: Terracotta carafe by Royal VKB

+	–
–Versatile production –Low cost –Natural wicking	–Not recyclable –Energy intensive to produce, though less so than many other ceramics

Production
As with many traditional ceramics, terracotta can be slip cast, turned on a lathe, jigger jolleyed and formed on a potter's wheel.

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be re-moulded. However, they can be crushed and used as fillers and gravel for various industrial applications. Due to the fact it fires at a relatively low temperature and is unglazed, terracotta is less energy intensive to produce than many other ceramics.

Cost
Relatively inexpensive.

Typical applications
In India, chai was served to railway passengers in terracotta cups, which were then thrown out of the window when the chai was drunk. Another unusual application exploits the acoustic properties of ceramics, resulting in the use of terracotta in speakers. More general applications include it being used as a material for exterior applications such as tiles, plant containers and hollow building bricks because of its ability to withstand frost. Apart from the bottle shown here, it is also used in wine bottle coolers, where soaking the terracotta in water naturally cools the wine.

Key features
- Wicking effect
- Straightforward to form
- Low cost
- Low density
- Porous
- Low firing temperature

Sources
Terracotta is a widely available clay, and can be found in various parts of the globe.

Cement

Hardcore was the name of an exhibition of concrete at the Royal Institute of British Architects in 2002, its subtitle was 'concrete's rise from utility to luxury'. It was a unique exhibition that highlighted concrete's huge, but often unknown, range of associations. It explained how, over the last 100 years, concrete has had a huge effect on our environment and that it is constantly being redefined in both its functions and associations.

Cement is one of the main ingredients of concrete and occupies its biggest use. It is a mixture of limestone, clay and shale. By adding water the powder is set and can be used for moulding. If too much water is added, the hardness of the cement is reduced and if too little water is added, the chemical reaction does not fully take place and the cement will not harden. The most common form of construction cement is Portland cement. When set it forms a stone-like material and its biggest application is in the construction industry.

Designers such as Alexa Lixfeld have helped to reposition the perception of concrete from utility to luxury through a range of tableware. The Swiss designer Nicolas le Moigne has collaborated with fibre cement company, Eternit to create 'trash cubes' a project that uses raw, recycled material to produce new stools.

Image: Trash Cube by Nicolas le Moigne with Eternit

+	–
–Incredible compression strength –Easy to cast –Can achieve a range of colours and effects –Recyclable	–Energy intensive to produce –Environmental concerns –High production costs

Production
Production of cement is nearly always based on casting into moulds, with Portland cement having a setting time of six hours and a compressive strength that increases and reaches a maximum strength over a period of weeks. Ciment Fondu®, another form of cement, sets much faster.

Sustainability issues
According to an article in *The Guardian* newspaper in 2007 'cement is emerging as one of the major obstacles on the world's path to a low-carbon economy'. This statement is based on several factors of cement production, including the heat and coal used to supply kilns during the production of cement and the release of carbon dioxide (estimated to be 5 billion tons annually by 2050), a by-product in the extraction of limestone. There are more and more companies who are looking at recycling concrete as rubble. It also contains chromium, which contributes to its toxicity as a skin irritant.

Typical applications
The biggest application for cement is in concrete, and the majority of concrete is used for building applications. Concrete is a mixture of cement, sand and an inert aggregate, which can be any number of materials but is usually small stones. However, various artists and designers have been exploring new possibilities for the material and new applications have been discovered that include jewellery, furniture, kitchen work surfaces and tableware. Cement is also used in other forms of construction, for example in grout.

Sources
After water, cement is the most used product on the planet, China produces half of all cement.

Cost
Relatively low cost, though production costs are high.

Key features
- Exceptional compression strength
- Different aggregates for a range of effects
- Colour can easily be changed
- Fairly low-cost tooling
- High labour cost

Derivatives
–White and grey Portland cement
–Ciment Fondu®. Compared to Portland cement, which is based on silica and limestone, Ciment Fondu has a range of advantages. It can be used to form far more complex shapes and to withstand temperatures up to 2000ºC (3632ºF) compared with 500ºC (932ºF) for Portland cement. It is also much more durable. It is a superior cement and is available in rich chocolate coloured and dark grey tones, or even a highly polished white. It offers the designer far more potential to experiment with the decorative and aesthetic qualities of cement than Portland cement does.
–Eternit is a fibre-based cement that has recently been explored through a number of design projects. It is 100% recyclable.

Granite

Granite has come to be defined by the qualities of ruggedness and hardness, terms that it justly deserves. Visually, it lacks the fine grain of marble, instead the oaty, coarse mosaic grains that are typical of granite give an insight into its ingredients and its structure; it is made of up of mica (the shiny bits), feldspar and quartz. Granite is an igneous rock, a family of rocks made through the solidification of molten magma or lava cooled slowly under great pressure.

Granite comes in many forms and these are characterized by colour variations. As a material, it is distinguishable by its hardness, durability and ability to weather well, even when compared with other stones, such as marble. For example, as a building material, it can be enhanced by polishing to emphasize its crystals, creating a glass-like surface that it will retain for many years, even in external applications. Its density is similar to marble and quartz, but compared to marble it is much harder – granite has a Shore Hardness of 85–100, whereas marble's is 45–56. It also has a much harder abrasive hardness, although well below that of quartz, and this is one of the reasons that it is so popular in kitchen countertops.

Image: Plus One salt cellar by Norway Says for Muuto

+	–
–High wear resistance –Polishes to a glassy finish –More durable than marble	–Expensive to mine and manufacture –Production has a high failure ratio

Production
Hand-cutting, sandblasting, CNC cutting, laser cutting and water jet cutting.

Sustainability issues
Granite is obviously a non-renewable resource, and strip mining can cause harm to the environment through chemical pollution to air, earth, and water. Measures are being taken to limit wastage during mining and manufacture, and an increasing number of companies now offer recycling options.

Cost
Due to the hardness of the material the production has high failure ratio, with only a small proportion being sold. This combined with the hardness of the material makes it expensive to manufacture and mine.

Key features

- High wear and abrasion resistance
- High density and hardness
- Polishes to a glass-like finish
- Each piece is decoratively unique
- More durable than marble

Typical applications

Flooring tiles, kitchen countertops, gravestones and, due to its flatness and resistance to damage, in engineering applications to obtain a plane of reference for measurement. It is also used for roadside bollards and other architectural elements.

Sources

Granite is mined in various countries; the main ones include the UK, parts of Scandinavia, South Africa and Brazil.

Marble

For thousands of years marble has held a reputation as a grand material, its use in sculpture and building widespread. In a geological context there are three general types of rock formations: igneous, rocks formed through the solidification of molten magma or lava; sedimentary, formed by rock particles broken down by the action of weathering and cemented together over thousands of years; and metamorphic. Metamorphic rocks are those that have mutated from one rock type to another over prolonged time. Marble is one such rock, metamorphosing from limestone – or calcium carbonate.

Marble can be richly veined or a cold, matt white material which, when cut thinly, is capable of creamy translucence, but in either form it is an evocative material. The fine crystalline structure of marble – when compared to the visibly large grain of a rock like granite – distinguishes it from other materials. It is this fine structure that makes it good for carving and such a popular material for sculptures.

Veined marble has a consistent pattern throughout its thickness, which allows for adjacent slabs to be mirrored in order to match patterns; this characteristic is often used in architecture. Although it is a relatively hard, dense material it is not as resistant to abrasion nor does it have the hardness of granite, in fact, for a stone it is relatively soft, another reason why it carves so well into the beautiful sculptures that help define this material as one of luxury and decadence.

Image: Tilt table by Thomas Sandell

+	–
–High density and hardness –Premium associations –Very good for carving	–Expensive to mine and manufacture –High failure ratio of production –Low wear resistance –Low chemical resistance

Production
Hand-cutting, sandblasting, CNC cutting, laser cutting and water jet cutting.

Sustainability issues
The production and transportation creates a large carbon footprint as well as environmental destruction.

Key features
Compared with other stones:
- Low wear-abrasion resistance
- Low chemical resistance
- Less durable than granite
- Each piece is unique, although it is easier to match patterns than for granite
- High density and hardness
- Polishes to a glass-like finish
- Fades over time due to weathering
- Premium associations
- Porous

Typical applications
Marble Arch, the famous London landmark, is made from Carrara marble – a white marble named after the Italian region where it is mined. Other applications are sculpture and gravestones – although marble is not as hard-wearing as granite – and architectural elements.

Sources
The UK has a number of quarries where marble is excavated, but Italy, Greece, Portugal and Scandinavia are all origins of marble.

Cost
As with other stone materials the hardness and the quarrying involved in production has high failure ratio, with only a small proportion being sold. This combined with the hardness of the material makes it expensive to mine.

Glass Ceramics *(aka Vitro Ceramics)*

How does a material translate into a consumer experience? Or how can a material's functionality be exploited to create an emotional response? The case of glass ceramics provides the answers. The early-to-mid part of the twentieth century marked a new age in materials. Not just because it witnessed the introduction of so many new types of materials – Nylon, Teflon®, Pyrex® – but also because it marked the point at which stories of the future were based on the promise of these new materials.

One of the success stories from this period was glass ceramic, a 'super material' that combined the properties of glass and ceramic, notably to produce a resistance to thermal shock. In addition to this property, and in comparison to conventional glass, glass ceramics are highly impact- and scratch resistant.

For the 1950s housewife this material meant ovenware that allowed her to take dishes straight from the freezer into a hot oven. For marketeers this could be translated into 'convenience'. The invention of CorningWare, alongside brands like Tupperware, meant that life in the 1950s was going to be liberated from tiny inconveniences. Glass-ceramics also provided a material for use in flat covers for kitchen hobs that eliminated the clunky cast-iron hot plates and rings that everyone was used to. For the modern consumer this translated into an 'easy clean' surface.

Image: Marc Newson hob for SMEG with Schott Ceran® glass

+	–
–Versatile processing –High thermal-shock resistance –High impact strength –Scratch resistant	–Comparatively expensive –Some glass ceramics use heavy metals in their production, causing environmental concerns

Production
Glass-ceramics can be pressed, blown, rolled or cast and then annealed. Up until this point the glass is virtually the same as normal glass. During the second phase the moulded products are subjected to a specific temperature and go through a process known as ceramification, which means they are formed into a polycrystalline material.

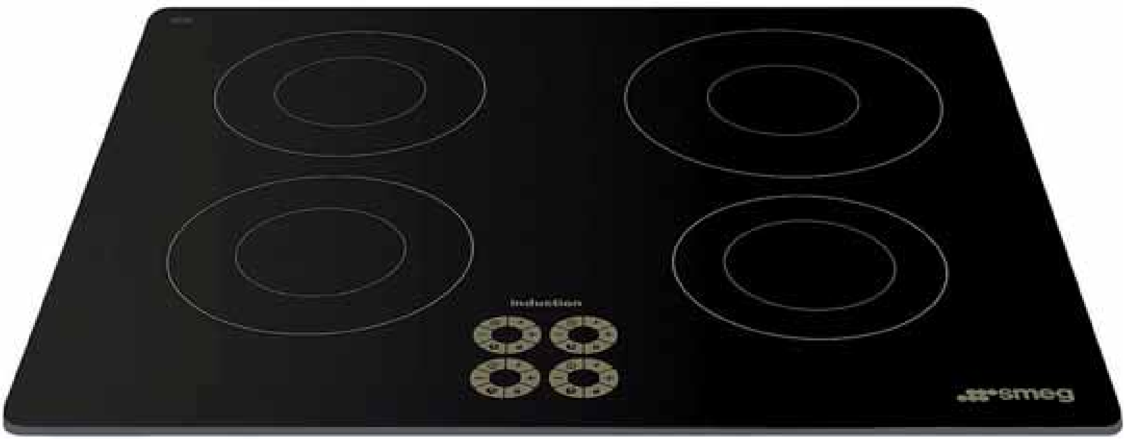
Typical applications
It's said by Corning Glass that the material came out of missile nose cones, which needed to withstand high temperatures. That one of the scientists working at Corning in idyllic Upstate New York took a sample home, where his wife preceded to experiment with cooking dinner in the sample, only to discover its properties were just as useful for cooking as they were for sending missiles into space. Beyond these two applications glass-ceramics are also used for windows for gas and coal fires and as mirror substrates for astronomical telescopes, which take advantage of its low thermal expansion.

Key features

- High thermal shock resistance
- High impact strength
- Extreme heat resistance
- Virtually no thermal expansion
- Translucent or opaque

Derivatives

One of the major players in the glass-ceramic industry is Ceran®, produced by Schott, which is one of leading brands in glass-ceramics for cooking tops. Such is the popularity of this non-porous cooking surface that is also promoted as an indoor barbecue, which can be cooked on directly.



Sustainability issues

Some glass-ceramics are produced with the use of heavy metals.

Cost

Relatively expensive.

Sources

Major global glass suppliers, such as Corning, Schott and Saint Gobain all produce various forms of glass ceramics.

Aluminium Oxide *(aka Alumina)*

First things first, metal oxides, of which alumina and zirconia are two, are not metals. For example, rust – iron oxide – is not the same as iron metal. Secondly, it's worth noting the naming of these materials, a formula whereby the suffix '-ium' is replaced by '-a'. Therefore, aluminium oxide is often called alumina and sits firmly within the ceramics family of materials.

Ceramics have undergone a massive evolutionary change over the last 40 years in relation to their performance and applications. The associations that ceramics have with craft, brittle china and terracotta still exist, but the new breed of technically advanced ceramics infuses new life and new associations into this primordial material.

Distinguished by hardness – ceramic knives don't lose their sharp edge as easily as metal – inertness and stiffness, ceramics are moving into the territory of metals. Such is the allure of advanced ceramics that designers have, since the commercialization of advanced ceramics, been looking at ways to introduce them into applications that range from cars to mobile phones. The biggest obstacles to this being production costs and the tolerancing of small components, which need to fit with a plastic injection moulding. Alumina and zirconia are two of the most widely used advanced ceramics and are helping to morph the definition of ceramics into a material of advanced technology and luxury when applied to consumer-facing design.

Image: Vertu's Constellation mobile phone with monocrystalline aluminium oxide screen

+	–
–Strong and tough	–Brittle
–Versatile processing	–High cost
–Extremely hard	–Not recyclable
–Good wear resistance	
–Widely available	

Production
Alumina can be extruded, dry – powder – wet compression moulded and sintered from powder. It can be machined, including diamond grinding, in its fired form. When formed and sold as a flat sheet it can also be laser cut. Due to this, variations on production of alumina are suited to both one-off and high-run batch or mass production. It can be readily joined to metals using metallizing and brazing techniques.

Sustainability issues
As an inert material, ceramics do not degrade. In order to produce ceramics an irreversible chemical reaction needs to take place, therefore, unlike thermoplastics, which can be reheated and reused, ceramics are not recyclable in the sense that they cannot be remoulded. However, they can be crushed and used as fillers and gravel for various industrial applications.

Key features

- Versatile processing
- Excellent hardness
- Good corrosion resistance
- Good stiffness
- Good thermal stability
- Excellent electrical insulation
- Higher resistance to wear than zirconia
- Brittle
- Expensive, but less than zirconia
- Melting point: 2072ºC (3700ºF)

Cost
£3.20 ($5) per kg.

Typical applications
Alumina is one of the most popular advanced ceramic materials. Used as an electrical insulator on spark plugs, its good wear resistance makes it ideal for parts, such as dies, bearings and, of course, kitchen knives. Its wide availability and its range of properties also make it suitable for electronic substrates and for making ceramic fibres and papers. It is also used for bulletproof vests and replacement ball-and-socket hip joints, where its wear-resistance means that small particles that are usually produced by metal replacement joints and which cause resistance are not created. It is also used in high-end mobile phones from Vertu and also for watches from Rado.

Sources
Alumina is one of the most widely available advanced ceramics and is obtainable in a range of purities to suit different applications. Australia has by far the largest reserves of bauxite, the principal ore of aluminium oxide.

Derivatives
Zirconia toughened alumina (ZTA) is used in mechanical applications. It is considerably higher in strength and toughness than alumina. This is as a result of the stress-induced transformation achieved by incorporating fine zirconia particles uniformly throughout the alumina. Typical zirconia content is between 10 and 20%. As a result, ZTA is more expensive than alumina but offers increased component life and performance.

Silicon Carbide *(aka Carborundum or Moissanite)*

Silicon carbide was first synthesized by accident in the late nineteenth century while trying to replicate real diamond – an occupation that was fairly common around that time and which led to a number of new carbides and nitrides – materials that offer the hardest alternatives to diamond – being discovered,
It appears to have been discovered simultaneously by American inventor Edward G. Acheson and chemist Henri Moissan. A blend of sand (silica) and carbon, silicon carbide, like diamond, is distinguishable by its incredibly hard-wearing properties. It maintains its shape at temperatures over 1000°C (1832°F) and has very high resistance to thermal shock, a property that allows it to go quickly from one extreme temperature to another without damage.

Although it's not a particularly new material it has been used in powdered form to create a brutally coarse, hard, dark green/grey stone-like material used as an abrasive for more than 100 years. It is used for its hardness in abrasive machining processes such as grinding and honing. As an offshoot of Moissan's discovery, Moissanite – another form of silicon carbide – was discovered and marketed as a gemstone with a hardness that approaches that of diamond but with greater clarity, contributing yet another story to the increasingly varied world of ceramic materials.

Image: Silicon carbide grinding stone

Production
Silicon carbide can be processed using a number of diverse techniques. These include using the powdered form for dry pressing (which is suited to batch production), sintering, ceramic injection moulding, isostatic pressing, extrusion and slip casting (for producing thin-walled hollow shapes). It can also be machined and ground with diamond wheels. Silicon carbide fibres are also used as reinforcement for plastics to increase strength, stiffness and wear resistance.

Sustainability issues
Silicon carbide is considered a hazardous substance in its crystalline state, and can cause irritation to eyes, skin and lungs as well as damaging the environment.

+	–
–Versatile processing –Extremely hard and strong –High thermal conductivity	–Only available through specialist suppliers

Cost
Price varies widely as there are many grades of silicon carbide, but it is generally a cost effective option.

Key features
- Very high resistance to wear
- High resistance to thermal shock
- Excellent hardness
- Excellent compression strength
- Low thermal expansion
- High thermal conductivity
- High chemical inertness

Typical applications
A main area of application is grinding media in environments where there are extreme changes of temperature and high wear and tear. These applications are based in heavy industry in objects such as seals and bearings, and turbine components. As well as Moissanite's use in jewellery, another main consumer application is car brake pads; the Porsche Carrera is one car that exploits its qualities, creating a compelling high-tech story. Silicon carbide fibres can also be added to plastic mouldings to increase hardness of parts.

Sources
Available through specialist global suppliers.

Boron Carbide

In terms of compression strength, ceramics are probably the strongest materials on Earth, which is why we still use clay bricks as one of our main building materials. Beyond buildings and other established applications of traditional ceramics, there are an increasing number of uses of ceramics for consumer products that employ a growing sub-group known as advanced ceramics. Most of these lay under the skin of products rather than as part of the surface design, but the introduction of advanced ceramics, such as alumina and zirconia, into domestic consumer products highlights how they are beginning to find their way into new product arenas. The functional benefit of advanced ceramics is their extreme hardness and resistance to wear in addition to the value they bring to the consumer as an advanced technology.

However, even within the context of hard ceramics, boron carbide is serious stuff, being the third hardest material known to man. This dark grey/black material, with the ability to be polished to such a high degree that it creates a mirrored surface, is the kind of stuff 1950s science fiction writers might have imagined flying saucers being made from. Apart from being one of the hardest materials available, when exposed to a temperature above 1100°C (2012°F) and not exposed to air, it is even harder than diamond, although much cheaper and far more versatile. As such, it is one of the relatively new ceramics that is changing the perception of this ancient family of materials.

Image: Kershaw boron carbide-coated knife

+	–
–Incredibly hard and strong –Versatile processing –Good wear resistance –Can achieve a high polish	–High cost so mainly limited to specialist applications

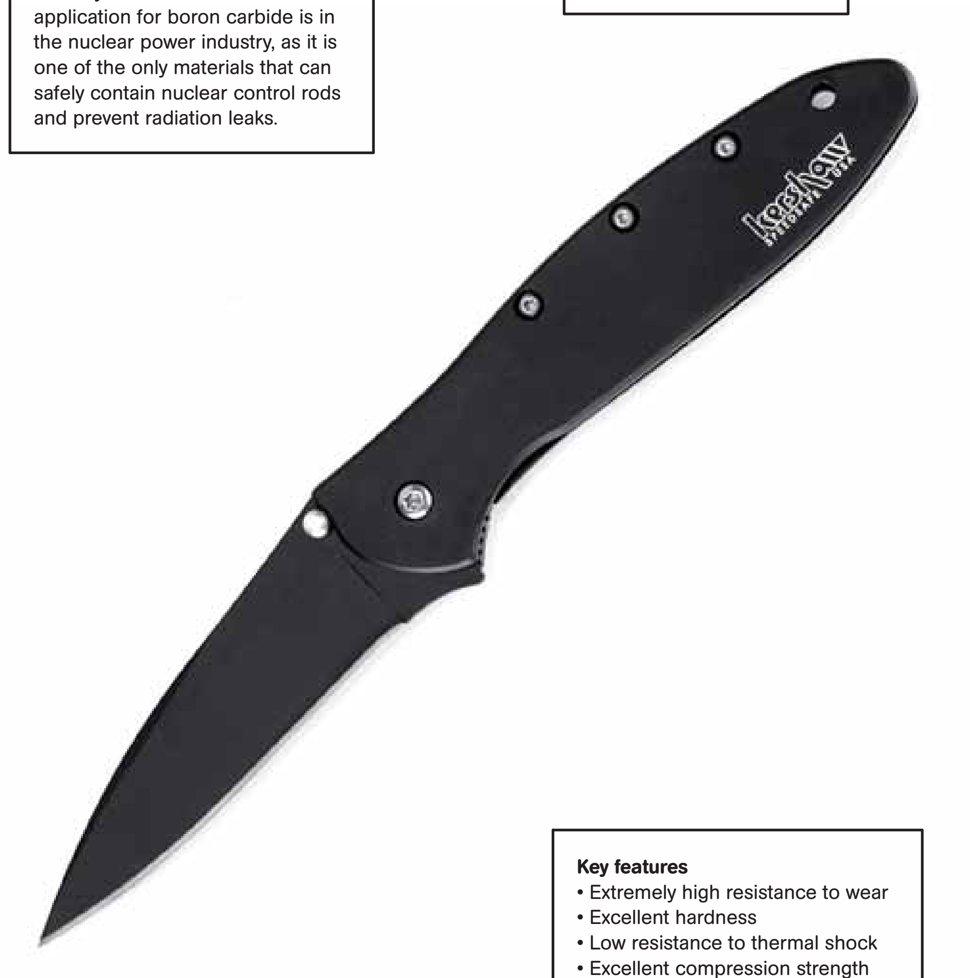
Production
Boron carbide can be processed using a number of surprisingly diverse techniques. These include conventional ceramic techniques such as dry pressing, isostatic pressing, which is suited to batch production, extrusion and slip casting for producing thin-walled, hollow shapes. It can also be machined and ground from a solid with diamond wheels to achieve complex shapes.

Sustainability issues
Boron carbide is non-toxic and chemically inert.

Derivatives
Tungsten carbide.

Typical applications
Many of the applications of boron carbide involve grinding media and severe environments where there is extremely high wear and tear. Naturally, these applications are based in heavy industry in applications such as seals and bearings, and turbine components. However, one of the most engaging uses is its application as body armour. A common application for boron carbide is in the nuclear power industry, as it is one of the only materials that can safely contain nuclear control rods and prevent radiation leaks.

Sources
Turkey and the USA are the world's largest producers of boron. Available through specialist global suppliers.



Key features
- Extremely high resistance to wear
- Excellent hardness
- Low resistance to thermal shock
- Excellent compression strength
- Can be polished to a mirror finish
- Low density in relation to other ceramics
- High chemical inertness and resistance to acids
- Less resistant to oxidation than silicon carbide

Cost
£50 ($78) per kg.

Silicon Dioxide *(aka Silica and Sand)*

Sand is hardly a material that is on a designer's radar. However it deserves a mention in this book due to two very different projects using it as a material from which new techniques of production have been born.

There is growing evidence to suggest that the future will be defined by new uses for old materials. An increasing number of inventors from design backgrounds have taken to scavenging the world of materials that are traditionally perceived more as substances than as materials. The bio-manufactured brick is a project developed in the deserts of the United Arab Emirates that uses bacteria combined with sand, salt and urea from animal urine (a common element in urea-formaldehyde plastics) to turn sand into a usable building element. Developed by Ginger Krieg Dosier of the American University of Sharjah, the process combines readily available ingredients to make a brick without the intense heat usually associated with making ceramics.

Another project that uses sand as a raw material is much more simple but no less inspiring. Developed by designer Markus Kayser, the SolarSinter project takes a machine powered exclusively by the sun and uses its energy to sinter – a process that uses heat to fuse fine particles together – sand into solid objects. Although this is a project more about a new manufacturing process rather than a material, it illustrates how designers are taking a lead in the search for alternative materials from which to make products.

Image: Better Brick project

+	–
–Extremely hard –High temperature and therma-shock resistance –Widely available	–Manufacturing processes still being developed

Production
Markus Kayser's sintering sand project takes the production of silicon dioxide into a whole new arena through its use of solar energy to fuse grains of sand. Another production method is based on a form of casting, where fibres of silica are suspended in water while being cast in a porous mould. As in slip casting, the water is drawn out leaving a dry, open-celled structure.

Sustainability issues
Sand is widely available and the case studies mentioned here use low energy to form the materials.

Key features
- Excellent hardness
- Non-conductive
- High resistance to thermal shock
- High temperature resistance - 1704ºC (3099ºF)

Derivatives
–Silica aerogel
–Glass
–Portland cement (around 24%)
–Silicon dioxide is found as quartz in granite
–Major ingredient in sandstone

Typical applications
Silicone dioxide is the dominant ingredient in glass making, glazing for ceramics and in cement. It is also used for its temperature resistance in space shuttle tiles, where a lightweight 0.028 cubic metre (1 cubic foot) block weighs less than 4 kg (9 lb).

Cost
Impossible to define precisely.

Sources
Silicon dioxide is one of the most common substances in the earth.

Silicon Nitride

The family of nitrides and carbides contains some of the hardest man-made substances, most of which are used in high-end engineering applications. Silicon nitride is generally off the radar when it comes to materials specified by designers. This may be partly due to the cost of some of these high-performance advanced ceramics, but also partly due to the fact that some of their characteristics have not travelled down the performance chain of consumer-facing products. However, this does not mean that they should not have a place in a designer's palette of materials.

Within the family of nitrides and carbides, silicon nitride is the third hardest material. Synthesized in the 1960s at a time when many new materials were being developed as a result of space exploration, silicone nitride was used to withstand the hostile environments endured by jet engines. Even within this family of super-strong materials, it stands out as having some incredible mechanical properties, including a very high compression strength of 4 million psi or, to put it another way, the ability to support the weight of 80 elephants balanced on a piece of silicon nitride the size of a sugar cube. It also has immense tensile strength: a 2.5 cm (1 in) diameter cable could lift 50 cars. And, in terms of surface smoothness, if a silicon nitride ball bearing were the size of the Earth, the roughest peak would be only be 6 metres (19 ft) high, the reason why it is so popular as a material for bearings.

Image: Silicon nitride ballbearings

+	—
–Incredibly high compression strength –High thermal shock resistance –High resistance to wear –Relatively lightweight	–Only available through specialist suppliers –Traditionally-processed silicon nitride is extremely expensive

Production
Like most advanced ceramics, silicon nitride can be processed using a variety of techniques. These include dry pressing (which is suited to batch production), ceramic injection moulding, extrusion, slip casting for producing thin-walled, hollow shapes and hot and cold isostatic pressing, It can also be machined and ground with diamond wheels.

Sustainability issues
New methods of fabricating silicon nitride parts by sintering is far more energy efficient than the conventional methods, because the process can shorten the processing time and reduce energy consumption.

Derivatives
–Hot isostatically pressed silicon nitride (HIPSN)
–Partial pressure sintered silicon nitride (PSSN)
–Pressureless sintered silicon nitride (SSN)
–Hot pressed silicon nitride (HPSN)
–Sintered reaction-bonded silicon nitride (SRBSN)
–Reaction-bonded silicon nitride (RBSN)

Key features

- Extremely hard
- High resistance to wear
- High resistance to thermal shock
- Excellent compression strength
- Three times harder than steel, but 60% lighter
- A friction rating that is 80% lower than steel
- Stiffer than most standard metals

Cost

The relatively high cost of silicon nitride in the past has limited it's application, but newly developed sintered silicon nitride is a far more cost-effective option.

Typical applications

This is a material that is far more effective and useful for its physical and mechanical properties than its visual. It is ideal for components working under mechanical loads and engine parts, especially at high temperatures. These include the main engine of the space shuttle, military missiles and gyroscopes. Other uses include bearings for saltwater fishing reels, racing bicycles, skates and skateboards.

Sources

Available through specialist global suppliers.

Zirconium Oxide *(aka Zirconia)*

Advanced ceramics form a large part of the new man-made luxury materials market. Partly because of the associations that come from their use in high-end engineering applications and partly because they do look very advanced. A quality that is derived from how they are finished and polished, which ranges from a smooth, matt, cold surface to mirror-like dark polished colours that look like coloured chrome.

This visual association is not the only link with metals. On a practical level, advanced ceramics have two distinct properties that result in them being used in applications where metals have previously been used. One of these properties is their hardness in comparison to metals, which tend to have edges that will soften much more quickly than advanced ceramics when used. As well as for kitchen knives, zirconia pressings are used for punching out aluminium drinks cans in industrial production. This improves efficiency and cost effectiveness because tools last for 20 months without showing wear, compared to two months for traditional metal tools.

Zirconia and alumina are two of the most widely used advanced ceramics, zirconia being similar to alumina but slightly tougher – less brittle – and with a greater resistance to wear. Like alumina, zirconia can be polished to achieve a mirror-like reflective surface that resembles polished metal. It also offers chemical and corrosion resistance to temperatures well above the melting point of alumina.

Image: Rado watch

+	–
–Excellent electrical insulation –Extremely hard –Corrosion resistant –Versatile processing	–Brittle –Lower resistance to wear than similar materials

Production
Zirconia, like alumina, can be extruded, dry – powder – wet compression moulded and sintered from powder. It can be machined, including diamond grinding, in its fired form. When formed and sold as a flat sheet it can also be laser cut. Due to this, variations on production of zirconia are suited to both one-off and high-run batch or mass production. It can be readily joined to metals using metallizing and brazing techniques.

Sustainability issues
Zirconium oxide is non toxic and unlikely to cause harm to the environment.

Typical applications
The smooth, fine surface finish that can be achieved with zirconia, combined with its toughness make it an ideal ceramic for cutting blades and kitchen knives. It is used in high-end mobile phones from Vertu and for watches from Rado. It is also used in car oxygen sensors, which utilize a form of electrically conductive zirconia.

Key features
- Versatile processing
- Excellent hardness, 50% harder than steel
- Good corrosion resistance
- Slightly higher density than alumina
- Excellent electrical insulation
- Readily joined to metals
- Lower resistance to wear than alumina
- Brittle
- High resistance to thermal shock
- Melting point: 2549ºC (46200ºF)

Cost
Price is dependent on grade, but is comparable with other high performance ceramics.

Sources
Alumina is one of the most commonly used materials in the advanced ceramic industries and is available in a range of purities to suit different applications.

Soda-lime Glass

Glass is not only a material that is defined by its transparency, but it is transparent in its contribution to the modern age, performing its duty as the backbone to the information revolution quietly, in the background of many of our daily routines. Glass is the base material on which many technologies are driving ahead: from the screens on our interactive, touch-sensitive phones, computers and tablets and the fibre-optic cables that carry masses of digital information to the more heroic, press-worthy products, such as glass that is self-cleaning or beautiful cut-glass.

By combining glass with other materials, such as plastics, we can enhance its properties and 'mend' some of its inherent flaws. Examples include glass that can block out UV-rays, glass that is bullet-proof or shatterproof , and glass fibres that can be added to plastics to enhance their strength.

Soda-lime is one of the most widely used forms of glass and the workhorse of the glass family, exploited for its hardness, transparency and chemical inertness. It is created by fusing several substances and silica ($SiO2$), in the form of sand, constitutes the largest part, with a mixture of sodium oxide (soda ash) (12–16 per cent), calcium oxide (lime) (5–11 per cent), magnesium oxide (1–3 per cent) and aluminium oxide (1–3 per cent) making up the other ingredients. The addition of the soda serves to reduce the melting temperature and that all-important transparency, with tinges of green, is the result of impurities in the ingredients.

Image: Lemon squeezer

+	–
–Versatile processing –Low cost –Good chemical resistance –Widely available –Recyclable	–Brittle –Poor thermal shock resistance

Production
Soda-lime glass is one of the most versatile types of glass in terms of production. It can be formed by hand to produce one-off art pieces, but is also suited to super high volumes and rapid rates of mass-production. Techniques used include hand blowing, either free-blown or blown into various types of moulds. It can be extruded, cast and cold worked by various cutting and engraving techniques and it can also be drawn into very fine fibres –fibre optics. The term 'float glass' is used to describe flat sheets of glass that have been made by being floated down a bath of molten metal.

Sustainability issues
According to the British Glass Manufacturers' Confederation, the energy saving from recycling a single bottle will power a 100-watt light bulb for almost an hour. As mentioned, the green tint that is present in much standard glass is due to iron impurities. In order to obtain a more brilliant sparkle, a small amount of barium is added.

Cost
Soda-lime glass is very inexpensive.

Derivatives
–Bohemian glass from the Czech Republic, known for its art glass, contains a large amount of lime and silica giving it a high clarity and brilliance similar to lead glass.
–Float glass

Key features
- Poor thermal shock resistance
- Low cost
- Good resistance to weathering
- Good chemical resistance
- Brittle
- Melts at 1500ºC (273ºF)
- Recyclable

Sources
Widely available.

Typical applications
Its impossible to narrow down the typical applications of soda-lime glass, because it is used in everything from window panes to milk bottles.

Borosilicate *(aka Pyrex®)*

Borosilicate is more a utility than a luxury type of glass. Although lacking the sparkle of soda-lime or crystal glass, this technical glass has still made a huge and unparalleled contribution to technology and our lives over the last 100 years. As the name implies, borosilicate glasses, the third major glass group, are composed mainly of silica (70–80 per cent) and boric oxide (7–13 per cent) with smaller amounts of the alkalis (sodium and potassium oxides) and aluminium oxide. The reason it is such an important glass is because of two of its main attributes, which are its high chemical resistance and its ability to withstand large changes in temperature.

Invented by Otto Schott, who went on to found Schott Glass, one of the giants of glass production, borosilicate glass is the material behind the global consumer brand Pyrex®, which was developed by the equally important US-based glass company Corning Glass in 1915. One of the most significant inventions of the twentieth century has to be the incandescent light bulb. Invented by Thomas Eddison in 1879, the lightbulb was only able to be mass-produced because of the invention of a ribbon forming machine, which was capable of producing the light in vast numbers, and because of the invention of a glass that was able to withstand the temperature variation between the inside of the lightbulb and the often freezing outside temperature. The ability of borosilicate glass to withstand thermal shock is what distinguishes it from the more common soda-lime glass.

Image: Arik Levy candleholder

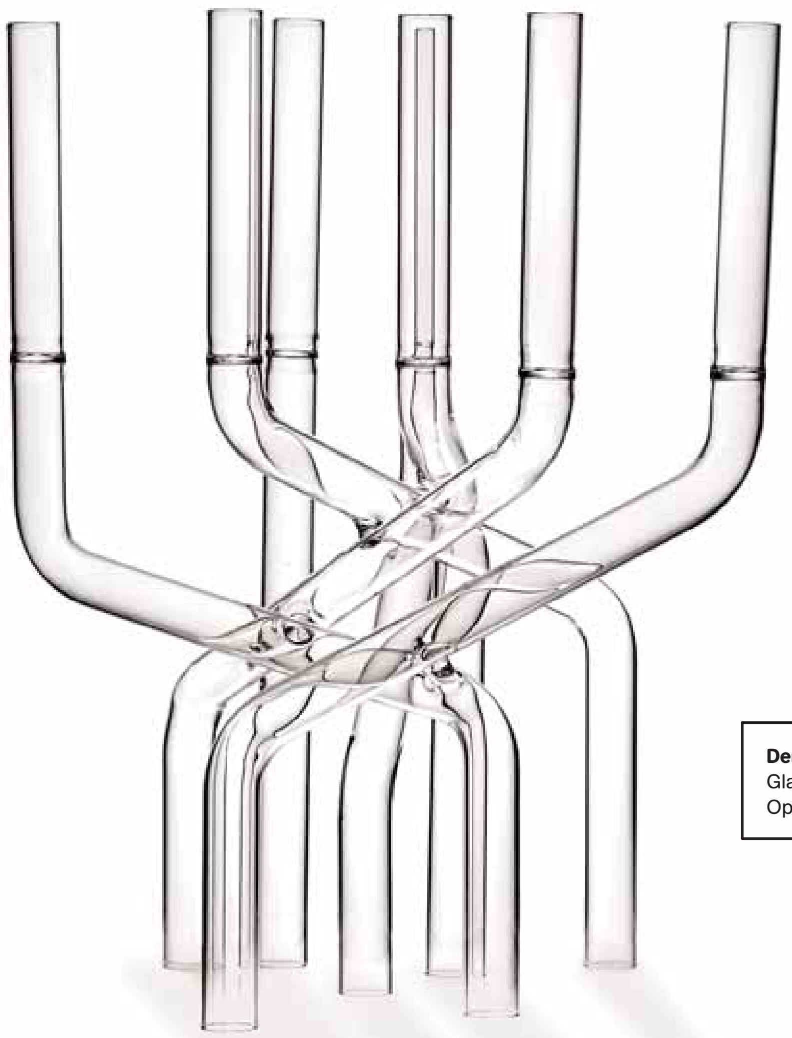
+	–
–Low production costs –High chemical resistance –High thermal-shock resistance –Comparatively strong	–Does not have the sparkle of some other glasses –Comparatively expensive

Production
It is a popular material within the low-production scales of some designers as it borrows the production methods of laboratory-ware. In these applications it can be formed without expensive tooling to produce multiples of the same shape. Often this process starts from a tube of glass and it is worked on a lathe. However, it can also be produced in high volume mass-production. Its comparative strength means that it has a greater potential for creating beautifully thin-walled, skeletal forms. Soda-lime glass is the nearest alternative to borosilicate glass. However, for more versatile production and greater ability to play with forms, then high clarity plastics, such as some copolyesters, polycarbonates, acrylics and certain types of styrenes or ionomer resins, are a good alternative. For thermal shock resistance, advanced ceramics are also worth exploring.

Sustainability issues
Exposure to water and acids only results in the leaching out of very small amounts of mainly univalent ions from the glass. The resultant, very thin, layer of silica with few pores that is formed on the surface inhibits further attack.

Sources
Widely available in various forms, including semi-finished sheets and tubes for lampworking.

Key features
- High thermal-shock resistance
- Less dense that soda-lime glass
- Stronger than soda-lime glass
- High resistance to chemicals, exceeding that of most metals even when exposed at 100ºC (212ºF) for long periods of time
- Low coefficient of expansion: this means virtually no stress takes place in the glass when, for example, boiling water is poured into it



Derivatives
Glass fibre
Optical glass fibre.

Typical applications
It is heavily used in the chemical industry for laboratory apparatus, pharmaceutical containers, high-intensity lighting applications and as glass fibres for textile and plastic reinforcement. In the home it is familiar in the form of ovenware and other heat-resistant ware, and is possibly better known under the trade name Pyrex®.

Cost
More expensive than soda-lime glass.

Lead Glass *(aka Crystal or Lead Crystal)*

Tupperware, made from HPDE, became a product defined by a 'burp', the sound the material made when you peeled away the lid and air was sucked into the soft, waxy container. Lead crystal is also a material defined through sound, in this case the 'ping'. Lead glass, or lead crystal as it is also known, signifies luxury, the resonance and 'ping' being the way most people assess its quality. It is associated with diamonds and pearls, ostentation and wealth. For anybody interested in chemistry, this is the result of the addition of lead oxide – 30 per cent for English full-lead crystal – which replaces the lime that is used in the more conventional soda-lime glass.

The introduction of lead into the recipe for glass results in the glass having a higher refractive index – brightness and sparkle – and a relatively soft surface in comparison to regular soda-lime glass. The resultant properties of clarity and softness, combined with the processes of grinding, cutting and engraving create the overall effect of a crystal-like glass. There are several ways of classifying the quality of lead crystal – which can be described under various terms, including crystal glass, pressed lead crystal, lead crystal and full lead crystal – that are dependant on the percentage of lead oxide; however, many people prefer to finger flick the glass and listen for that pure ring to test its quality.

Image: Stemware by Josef Hoffmann for Lobmeyr

+	–
–High clarity Easy to engrave –Easy to work –Less energy intensive to produce than other glasses	–Comparatively low rigidity –Relatively high cost –Poor thermal-shock resistance

Production
Lead glass can be processed using many of the techniques employed for soda-lime glass, including hand blowing, pressing and extrusion. However, its relative softness means that it is easier to work and one of the main processes used is cutting and engraving, which exploit its high clarity.

Sustainability issues
The lower temperature at which this type of glass is formed means that it requires less energy to form. Although lead is a known health risk and can cause lead poisoning, which affects the nervous system, the lead (there must be at least 24% for a glass to be classed as lead crystal) in lead crystal is locked into the chemical structure posing no health risk.

Key features

- High lead content
- One of the heaviest glasses
- Low rigidity compared to other glasses
- High refractive index so high clarity
- Relatively soft, so easy to engrave
- More expensive than soda-lime
- The 'ping'
- Not as good as borosilicate or glass-ceramic in thermal shock

Typical applications

Because of its clarity, it is often the choice material for drinking glasses, vases, cut-glass decorative tableware and ashtrays. But its use is not limited to fine crystal tableware, it is also used in optical components and neon tubing. Lead glass, with a typical composition of 65% lead oxide, is used in glass applications that require radiation shielding.

Cost

Relatively expensive

Sources

Widely available.

Aluminosilicate Glass

Aluminosilicate glass in the form of Gorilla® Glass is a culture changing material because our interactions with the world are increasingly taking place from behind a piece of glass, in the form of mobile phones, tablets, computers and TVs. Aluminosilicate is harder and more scratch resistant than polycarbonate, and increasingly it is being used to create display panels on technologies with touch capability. Our interactions with touchscreen devices are facilitated by materials that are able to withstand day-to-day scratches and yet are also thin and strong enough to fit into slim devices. And if the future is to be driven by data, then glass will start to replace even more materials.

The chemical strengthening process – know as the ion exchange process – plus the 20 per cent aluminium oxide within aluminosilicate glass is what propels ordinary soda-lime glass into a being a super glass with superior strength, resulting in the thinner glass that is used for display technologies. It is six times stronger than untreated soda-lime glass, it can bend like plastic, is scratch resistant and, because it is so strong, less glass is used and so it is much lighter than conventional glass. As one of the most prominent aluminosilicates, Gorilla® Glass – which is produced by Corning Glass®, who have been at the heart of many innovations in glass such as Pyrex® – is driving innovation in various display technologies and enabling interaction with data in previously unexplored applications.

Image: Samsung Galaxy with Corning® Gorilla® Glass

+	–
–Light and thin –Good scratch resistance –Excellent strength –Excellent chemical resistance –Versatile	–Only available in sheet form –Relatively expensive

Key features
- Superior scratch resistance
- Good flexing strength
- Superior strength
- Thinner and therefore lighter weight
- Excellent chemical resistance
- Only available in sheet form

Typical applications
Not limited to screens for phones, tablets and laptops, sheets of strengthened aluminosilicate can also be used glazing in automotive applications such a sun-roofs, display screens and glazing. In these applications the main advantage is weight saving. It can also be applied to kitchen appliances, such as fascias for refrigerators to take advantage of its scratch resistance and interactivity, and a range of interior applications including screens and elevator interiors to reduce weight.

Sources
Widely available from limited number a suppliers.

Cost
More expensive than standard glass.

Derivatives
Gorilla® Glass.

Sustainability issues
The lighter weight of this glass means that for automotive applications in particular it can contribute to more fuel-efficient driving.

Production
The nature of the chemical treatment process for sheets of aluminosilicate glass means that production is limited to processing methods that start with a sheet. Printing, laser cutting, folding and, to a degree, compound curves can be achieved with these materials. Sheets can also be laminated with each other and with plastics for enhanced strength.

Quartz Piezoelectrics

Piezoelectric materials are best described as materials that either generate an electric charge when deformed, by hitting or bending, or change their shape when an electric charge is applied to them. As such, they are one of the most prolific technologies in the growing area of smart materials, particularly in the area of energy harvesting. This mechanical strain at the heart of the technology can come from many different sources, but to illustrate the principle, placing a ruler on the edge of a desk and pinging it is a good example of the piezoelectric effect. If the ruler were made of piezoelectric material the vibration would produce electricity, which when attached to a light source will generate light.

The idea of piezoelectric materials is not new – mined from quartz, these smart crystals were discovered in the 1880s by Pierre Curie – but the development of materials that can convert enough electricity to be useful has been difficult until now. The web is full of ideas for exploiting the piezoelectric effect, from pounding feet on dance floors that generate power for video screens to scenarios where piezoelectric crystals in the road harvest energy from passing cars. Traditionally, generating electrical power has been an environmentally costly exercise, using fossil fuels, and with our search for alternative sources of energy, there has been a great deal of interest surrounding the use of piezoelectric materials to drive clean energy.

Image: Power Welly by Orange in collaboration with GotWind, renewable energy specialists

+	–
–Versatile –Smart material –Renewable energy source –Widely available	–There are no notable disadvantages

Production
One company, Advanced Cerametrics Inc, has developed a ceramic piezoelectric composite fibre that is much more flexible and can generate more electricity than the piezoelectric crystal. The idea behind this product is to find existing mechanical energy that is not being used and to 'harvest' and convert it into electricity.

Typical applications
Today, piezoelectric crystals are already in widespread use in cigarette lighters, kitchen gas lighters, microphones, sound generating devices for sonar and ultrasound detectors, tweeters in stereo speakers and quartz crystals in watches. Beyond these applications, the possibilities for this material appear to be endless. For example, the material can be incorporated into many applications where 'wasted' mechanical energy, such as vibrations, could be converted into useful energy by piezoelectric fibres. Imagine, for example, aircraft cabin lighting that is powered by the vibrations from the engines. Piezoelectric fibres have also been incorporated into footwear, so that hikers can recharge GPS devices by plugging them into a boot. At the Glastonbury music festival, piezoelectrics were installed inside wellington boots provided by the mobile phone network Orange to charge mobile phones.

Sustainability issues
The need to explore new sources of energy is propelling piezoelectics into the forefront of new ideas. The wide range of potential applications for converting movement into energy is one of the most innovative areas in which sustainability is being addressed.

Key features
- Generates electricity through vibration
- Changes shape when electricity is passed through it
- Naturally occurring phenomenon

Sources
Although quartz crystals are not the only piezoelectric materials, they are the most widely used. The number of companies who currently produce these materials is limited but is rapidly growing as energy harvesting technology grows in performance and demand. Quartz piezoelectrics can also be produced as synthetic crystals.

Cost
Quartz Piezoelectric crystals are relatively inexpensive.

Glossary

acetate
A chemical formed from reactions with acetic acid.

allotrope
A distinct form of an allotropic element, which can exist in different forms depending on molecular structure. For example, diamond and graphite are two allotropes of carbon.

anisotropy
Having different physical or visual properties along different axes.

antimicrobial
Capable of killing or inhibiting the growth of micro-organisms.

biomimicry
The deliberate imitation of biological processes in the solving of engineering or other complex problems.

bioplastic
Plastic derived from renewable sources such as vegetable fats, starch, proteins or microbes.

brogueing
Punching a pattern of holes into a material such as leather, as in brogue shoes.

BSE
Bovine spongiform encephalopathy. An infectious disease found in the nervous systems of cattle, which can be spread to humans and other animals through the food chain.

calendering
The use of rollers to make a material, typically paper, smooth and glossy at the final stage of manufacture.

carat
A measure of the purity of gold, with 24 carats equalling pure gold.

CFCs/HCFCs
Chlorofluorocarbons and hydrochlorofluorocarbons. Volatile organic compounds containing the elements chlorine, fluorine, (hydrogen) and carbon. Once widely used, they have been phased out due to their damaging effects on the ozone layer.

cites
The Convention on International Trade in Endangered Species of Wild Fauna and Flora, also known as the Washington Convention: an agreement in place since 1975 to ensure that international trade in wild animals and plants does not threaten their survival in the wild.

Class 1 fire retardant
England and Wales Building Regulations classify fire-retardant materials as Class O or Class 1, with Class O the stricter standard. One or other may be legally required depending on the specific usage.

commodity polymer
An everyday plastic used in high volumes at low cost. They are often used in packaging and disposable items.

composite
Material made from different components to combine their different properties. For example, concrete – a mixture of stones and cement.

deal
Softwood from coniferous trees when in use as a building material. Can also refer to a plank of such wood.

die-cutting
The process of cutting shapes from a thin, soft material, such as leather or card, using a metal die or cutter.

dioxins
Highly toxic by-products of a number of industrial processes, including the production of PVC.

ductile
Able to be bent, deformed or drawn into a wire by stretching.

electrospinning
The use of an electric charge to draw fibres from a polymer solution.

engineering polymer
A plastic with superior mechanical or thermal properties to everyday commodity polymers. They are used in smaller volumes and are more expensive to produce.

esters
Plastics, including polyester, derived from the chemicals of the ester group. 'Polyester' commonly refers to polyethylene terephthalate (PET), although it can technically refer to any of this group.

ethylenes
Plastics, including polythene (polyethylene), derived from the chemical ethylene, also known as ethene. They are the most commonly used group of plastics.

ferrous
Containing or consisting of iron.

forestry stewardship
The management and care of forests as natural resources, to ensure their long-term health and productivity.

grain
Can refer to the direction, texture or pattern produced by wood fibres.

hardwood
Wood from angiosperm (flowering) trees such as beech or oak.

heartwood
Wood from the inner part of a branch that has naturally become resistant to decay. Once formed it is effectively dead. Also known as duramen. *See also* sapwood.

high-performance polymer
A particularly hard-wearing and temperature-resistant plastic, used for specialized applications. Superior to both commodity polymers and engineering polymers.

hygroscope
An instrument used to measure humidity.

lamination
The binding together of two or more thin layers of different substances to combine their properties.

monomer
The simpler chemicals whose molecules are linked together to form polymers.

nanotechnology
The manipulation of matter on an atomic or molecular scale.

nitrate
A chemical formed from reactions with nitric acid.

non-ferrous
Not containing iron.

optical lithography
A printing process in which a pattern of light is projected on to a surface, causing a chemical to either bind to it or be etched from it in that pattern. Used in the production of printed electronic circuits and silicon chips. Also known as photolithography.

petrochemical
Any chemical product derived from petroleum.

piezoelectrics
The production of an electrical charge by placing certain materials, such as crystals, under mechanical stress.

pioneer species
A species that is among the first to recolonize a damaged ecosystem, such as birch trees at the end of the last ice age.

Poisson ratio
The ratio of a material's expansion (or contraction) along two axes to its compression (or extension) along a third axis when a force is applied to it. Ranging between -1 and 0.5, a high value indicates significant outward expansion. Cork has a value of 0, indicating that it does not expand outwards at all when compressed. Named after Siméon Poisson.

polymer
A substance that has a molecular structure built up from a large number of similar units bonded together. Examples include plastics and proteins. *See also*: commodity polymer, engineering polymer, high-performance polymer and ultra polymer.

polymerization
The process of producing a polymer from simpler chemical units, known an monomers.

press-forming
A technique in which sheets of a heated material, such as PVC, are formed against a solid mould in a mechanical press.

quarter cutting
A method of cutting boards from logs that begins with dividing the log in four lengthways, so that the grain in the resulting planks is more evenly distributed. Also known as quarter sawing.

rare earth elements (REEs)
A set of 17 elements, mostly from the lanthanide group, with a number of high-tech applications. While the elements themselves are not generally rare, forms of their ores at concentrations high enough to be mined are much harder to find.

retting
The use of water and microbes to remove a natural fibre from its stem, as used with hemp and flax.

sapwood
Wood from the outer part of a branch, which in a living tree is still growing. Also known as alburnum. *See also* heartwood.

Shore hardness
The hardness of a material as defined on a scale devised by Albert F. Shore.

softwood
Wood from gymnosperm (non-flowering) trees such as conifers.

spin coating
A process used to apply a thin film to a flat, solid surface. The film is applied in liquid form and spun at high speed until the surface is coated to the desired thickness.

steam bending
A technique in which steam is applied to wood, making it temporarily pliable. It is then bent or moulded into shape and held until it hardens.

styrenes
Plastics, including polystyrene, derived from the chemical styrene, also known as vinyl benzene or phenyl ethane.

superalloy
An alloy, usually of nickel, nickel-iron or cobalt, that possesses excellent strength, stability and resistance to corrosion.

tensile strength
The maximum stress that a material can withstand while being pulled before it breaks.

thermoplastic
A plastic which becomes pliable or mouldable when heated, and returns to a rigid state when cooled. Also called a thermosoftening plastic. *See also* thermoset.

thermoset
A plastic which, once set or 'cured', cannot be melted back

into a soft or liquid state. Also called a thermosetting plastic. *See also* thermoplastic.

ultra polymer
A loose term for plastics whose properties are considered or marketed as superior to other high-performance polymers.

urethanes
Plastics, including polyurethane, derived from the chemical urethane (also known as carbamate) linked with other organic compounds.

UV rays
Ultraviolet rays. Electromagnetic rays with a wavelength shorter than visible light and longer than X-rays. They are a component of sunlight and harmful to human skin when exposed in large quantities.

veneer
A thin surface layer of decorative, fine wood glued to a cheaper base. It can also refer to any fine sheet of wood, such as those used to make plywood.

vinyl chlorides
Plastics, including polyvinyl chloride (PVC), derived from the chemical vinyl chloride, also known as vinyl chloride monomer, VCM or chloroethene.

VOCs
See volatile organic compounds.

volatile organic compounds
Any of a diverse range of organic compounds that are gases at room temperature. They can be harmful if released in poorly ventilated areas, for example in paint fumes.

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167 Photography X R Kott
169 Spun, Heatherwick Studio, photo: Peter Mallet.
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173 Groove Bowl from Gleam Pewter Collection. Designed by Miranda Watkins (2007). Photography: Graham Pym
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