The Science of Ice Cream
3rd Edition

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Preface to the Third Edition

I was delighted when, nearly 20 years after the first edition of this book was published, the Royal Society of Chemistry asked if I would produce a third edition. However, while I retain my interest in ice cream, I no longer work in this area, so a co-author was required. Andrew Cox and I both joined Unilever as ice cream research scientists in the late 1990s. Andrew was one of the colleagues who helped me with suggestions for the first edition. He has worked on a wide range of ice cream projects, focusing on new ingredients, formulations, manufacturing processes and microstructure, so he was the obvious person to ask. Fortunately for me, he said yes.

The major developments in ice cream since the second edition was published have been in the area of "better for you" formulations, in particular reduced sugar, and in non-dairy, plant-based ice creams. This third edition therefore includes a new Chapter 8 to cover this, which also incorporates the section on improving the nutritional properties that was added to Chapter 7 in the second edition. Some new ingredients and experimental techniques have been added in Chapters 3 and 6, respectively. The other chapters have been updated as required.

We would like to thank the following people from Unilever R&D Colworth for their assistance with the new material: Damiano Rossetti and Alison Russell for providing additional

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images and technical information relating to confocal microscopy and non-dairy ice cream; Rachel Holland and Eva Kovacs for checking those parts of the text relating to nutrition and regulatory matters; and Peter Schuetz for technical information on microstructure and measurements.

Chris Clarke
Andrew Cox

Preface to the Second Edition

The second edition of *The Science of Ice Cream* incorporates the main developments in the ingredients and techniques used in ice cream that have taken place since the first edition was published nearly eight years ago. Chapter 7 has a new section which discusses the topic which has probably received the most attention in recent years: the challenge of reducing the fat, sugar and calorie contents of ice cream whilst maintaining its taste and texture. I have also added some extra material as a result of suggestions made by reviewers of the first edition. I would particularly like to thank Tom Coultate, Loyd Wix and Jeff Underdown for their help with the new material, and my family – now enlarged by the arrival of Oliver – for their support.

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Preface to the First Edition

The almost invariable response when people find out that I am an ice-cream scientist is: "What a great job! But is there science in ice cream? Do you invent new flavours?" As a physicist I don't invent new flavours, but my job does involve, amongst other things, inventing new textures. To explain this I normally briefly describe what ice cream is made of and how this relates to the texture you experience when you eat it. Fortunately, almost everybody likes ice cream, so, unlike most other areas of research in which I have worked, I usually manage to finish explaining the science before the listener's eyes glaze over. In fact ice cream is a great vehicle for talking about science. My colleagues and I regularly receive invitations to speak to schools, science societies and at events such as the Cambridge Science Festival and National Science Week. These talks have proved popular (I hope not only because of the free samples), and as a result I have received requests to write articles for journals such as Education in Chemistry and Physics Education, and to help with material for the Royal Institution Christmas Lectures. So when the RSC asked me whether I thought there would be a market for a book on *The Science of Ice Cream* I felt confident enough that there would be to agree to write one.

The aim of this book is to show that there is lots of science in ice cream, and in particular to demonstrate the link between

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the microscopic structure and the macroscopic properties. It is naturally biased towards physics, physical chemistry and materials science as these are the areas in which I trained. The book is aimed at schools and universities, and a scientific background is required to understand the more technical sections. I have attempted to make it readable by 16–18 year olds, and many sections are suitable for adaptation by GCSE science teachers. I have unashamedly made reference to giants of chemistry and physics such as Newton, Einstein, Boyle, Gibbs, Kelvin, Laplace and Young where the laws and equations that bear their names are relevant. I hope that as a result teachers reading this book will find in ice cream useful illustrations of a number of scientific principles. Some sections could be used with younger pupils, especially Chapter 8, which describes experiments on ice cream that can mostly be performed without specialist equipment in a classroom or kitchen. This book should also provide a useful introduction to ice cream for someone who has recently joined the food industry but I nonetheless hope that it will be accessible to any interested reader who is prepared to skip the most technical sections. I have included a glossary to explain the technical terminology.

I could not have written this book without the assistance of a large number of people. Firstly I would like to thank Unilever for permission to publish it. My colleagues at Unilever Colworth have provided data, images and suggestions. I am especially grateful to Laurie Bender, Allan Bramley, Deryck Cebula, Bruno Chavez, Andrew Cox, Paul Doehren, Viki Evans, Dudley Ferdinando, Dick Franklin, Andy Hoddle, Martin Izzard, Danny Keenan, Mark Kirkland, Linda Jamieson, Dan Jarvis, Jean-Yves Mugnier, Tricia Quail, Andrew Russell, Susie Turan and Paul Trusty. Javier Aldazabal from CEIT, San Sebastian, Spain, WCB Ice Cream, and the London Canal Museum kindly supplied images. Elsevier Science, IOP Publishing Ltd, Microscopy and Analysis and The Royal Society of Chemistry gave their permission to reproduce previously published material. Finally I would like to thank my wife Alexandra for reading the draft, my mother Lorrie and my niece Charlotte for trying out the experiments and my son Theo, whose arrival nearly provided sufficient impetus for me to finish the book!

Author Biographies

Chris Clarke has a degree and PhD in physics from Cambridge University. After post-doctoral work on the properties of polymers and colloids at surfaces and interfaces in Cambridge and at McGill University, Montreal, Chris joined Unilever, first as a research scientist in the Ice Cream Group, and then as a patent attorney responsible for Unilever's ice cream patents. He has given talks on ice cream science at various schools and universities, as well as at the Royal Institution, the Science Museum and the Cambridge Science Festival. Chris left Unilever in 2013 and currently works on formulations and devices for inhaled medicines, but retains an interest in ice cream.

Andrew Cox has a PhD in chemistry from the University of Bristol, where he studied the properties of polymers and colloids. He then joined Unilever as a research scientist in the Ice Cream R&D Group, where he has worked on many projects relating to building ice cream ingredient and formulation capability, supporting innovation and sustainability programmes around the world. Andrew is an inventor on over 20 patents. He is based in Colworth, UK, but also spent 3.5 years working for Unilever's ice cream business in North America.

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Glossary

Ageing: a step in the manufacturing process in which a pasteurized, homogenized mix is held at about 4 °C for a period of several hours. During this time, some of the fat crystallizes and some of the protein coating on the fat droplets is replaced by emulsifiers.

Attribute: a term used for one aspect of the sensory properties (*e.g.* firmness, smoothness, iciness) used in analytical sensory measurements.

Coarsening: the increase in the mean size and the reduction in the number of particles in a colloidal dispersion at constant total volume, thereby lowering the energy.

Composite material: a material obtained by combining two or more component materials on a microscopic or macroscopic level (*i.e.* not at the molecular level). The components do not dissolve in each other and the interfaces between them can be identified.

Compound chocolates: chocolate analogues made with fats other than cocoa butter (*e.g.* coconut oil). Compound chocolates have a wider range of textures than chocolate and can be flavoured (*e.g.* with lemon, strawberry or yoghurt). They are also sometimes known as couverture, but this can be ambiguous because the term “couverture chocolate” also refers to chocolate that has a high cocoa butter content.

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Contiguity: a measure of the connectivity of one phase in a composite material.

Dasher: a mixing device that rotates inside the barrel of a scraped surface heat exchanger and to which scraper blades are attached. The dasher has two functions: to scrape ice crystals off the barrel wall and to shear the ice cream as air is injected, thereby breaking up large air bubbles and mixing in the ice crystals. Dashers may be open (*i.e.* they occupy a small proportion of the volume of the barrel, typically 20–30%) or closed (*i.e.* they occupy a large proportion of the volume, typically 80%).

Destabilized (de-emulsified) fat: fat which has undergone partial (or total) coalescence so that it is no longer in the form of a fine emulsion.

Dextrose equivalent (DE): a measure of the extent to which the polysaccharides in corn syrups have been broken down into smaller molecules. The higher the DE, the lower the average molecular weight. Glucose (dextrose) has a DE of 100 and starch has a DE of 0.

Eutectic mixture: the specific mixture of two compounds that has the lowest melting point of any such mixture. Eutectic mixtures (unlike other mixtures) melt and freeze at a constant temperature, called the eutectic temperature.

Factory freezer: a scraped surface heat exchanger in which the first stage of ice cream freezing takes place.

Failure mechanism: the manner in which a material breaks (fails) when it is deformed. Water ices typically undergo rapid, brittle failure, whereas ice cream typically undergoes more gentle, plastic failure.

Freeze-concentration: the process by which a solution becomes more concentrated as it is frozen. The ice formed excludes the solute molecules. Thus, as freezing proceeds, the number of water molecules in the solution decreases, but the number of solute molecules does not, so it becomes more concentrated.

Glass transition: when, for example, a sucrose solution is cooled down, it becomes more concentrated due to freeze-concentration. Because the sucrose does not crystallize easily, the solution becomes very viscous and, as it is cooled, the molecular motion becomes very slow. Eventually the molecular motion effectively stops and the viscosity becomes so large that the solution effectively becomes a solid. However, unlike a crystal, the molecules are not ordered on a lattice, but have a disordered liquid-like structure, known as a glass. The change to a glassy solid is known as the glass transition.

Hardening: the second freezing step in the manufacturing process in which partly frozen ice cream from the factory freezer is placed in a very cold environment to cool it down rapidly to a temperature at which the coarsening of ice crystals and air bubbles is halted and the ice cream is hard enough for further processing, such as dipping in chocolate.

Hydrogen bonding: a strong intermolecular attraction that occurs between hydrogen and oxygen atoms.

Inclusions: pieces of fruit, nuts, chocolate, biscuit, cookie dough, marshmallow or toffee that can be mixed into ice cream.

Matrix: a viscous solution of sugars (and, where present, other ingredients such as stabilizers, milk proteins, flavours and colours) that forms the continuous phase in which the ice crystals (and, where present, air bubbles) are dispersed.

Meltdown: an empirical measure of the rate at which ice cream melts when exposed to warm temperatures, usually determined by measuring the amount of melted ice cream that drips through a wire mesh as a function of time in a temperature-controlled environment.

Milk solids non-fat: all of the components of milk other than water and fat (*i.e.* protein, lactose, vitamins, minerals and other minor constituents).

Mix: a blend of the ingredients of ice cream or water ice prior to freezing.

Mono-/di-/tri-/oligo-/polysaccharide: a molecule consisting of one/two/three/several/many saccharide units. Monosaccharides are the simplest sugars and conform to the chemical formula $(CH_2O)_n$, where n is from 3 to 7 and most commonly 6.

Mono-/di-/triglyceride: a molecule consisting of one/two/three fatty acids esterified to a glycerol molecule. Mono- and diglycerides are emulsifiers, whereas triglycerides are fats.

Overrun: a measure of the amount of air in ice cream defined by: (volume of ice cream − volume of mix)/volume of mix, expressed as a percentage.

Partial coalescence: when two fat droplets that contain some solid and some liquid fat coalesce, they form a cluster that retains some of the individual nature of the original droplets. Thus they coalesce, but only partially.

Percolation: a microstructure in which a continuous path can be traced from one side of the material to the other in a single phase is said to be percolated – for example, the ice crystals in a high ice content water ice.

Polyelectrolyte: a polymer that dissociates on dissolving in water to give a multiply charged polymer and an equivalent amount of ions with a small charge of the opposite sign.

Propagation: the growth of ice crystals as the temperature is lowered during hardening, accompanied by an increase in the total ice phase volume.

Quiescent freezing: freezing without agitation, used, for example, in the production of some moulded water ices.

Recrystallization: the coarsening of ice crystals (*i.e.* the increase in the mean size of ice crystals at constant ice phase volume).

Relative sweetness: the sweetness of a substance (such as a sugar, sugar alcohol or high-intensity sweetener) compared with that of sucrose, where sucrose has a relative sweetness of 1.

Residence time: the length of time that an ice cream mix spends inside the barrel of a factory freezer.

Scraped surface heat exchanger: a class of equipment designed to remove heat from viscous liquids. Scraped surface heat exchangers normally consist of a cylindrical barrel, the outside of which is cooled. The inside of the barrel is scraped to remove the solidifying material and thereby increase the heat flow.

Slush-freezing: freezing with agitation (*e.g.* in a factory freezer).

Wheying off: the phase separation of milk proteins and stabilizers in the matrix.

Symbols

a	Absorbance
A	Area
b	Constant in a power law fluid
B	Breadth
C	Contiguity
d	Displacement
D	Depth
E	Energy
F	Force
g	Gravity
G'	Storage modulus
G''	Loss modulus
h	Height
H	Hardness
l	Length
L	Latent heat
m	Mass
n	Number
P	Pressure
Q	Heat
r	Radius
R	Gas constant
S	Span

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t	Time
T	Temperature
v	Velocity
V	Volume
x	Mole fraction
Y	Young's modulus
γ	Surface or interface tension
$\dot{\gamma}$	Shear rate
ε	Strain
ε_y	Yield strain
η	Viscosity
η_1	Intrinsic viscosity of solvent
ρ	Density
σ	Stress or shear stress
σ_y	Yield stress
ϕ	Volume fraction

Disclaimer

The Royal Society of Chemistry is not responsible for individual opinions expressed in this work and does not endorse or recommend the products mentioned herein. Other products are also available. Products should be used in accordance with the manufacturer's instructions.

Readers should be aware that the products discussed in this book were those that were available in the UK in 2024. The ingredients in current versions of these items may be different.

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CHAPTER 1

The Story of Ice Cream

1.1 WHAT IS ICE CREAM?

Ice cream is an enormously popular food. The term "ice cream" in its broadest sense covers a wide range of different types of frozen dessert. The main ones are:

- Dairy ice cream – a frozen, aerated mixture including dairy ingredients (*e.g.* dairy milk protein and cream), sugars and flavours.
- Non-dairy ice cream – made without any dairy ingredients using proteins from plant sources and vegetable fats.
- Gelato – an Italian-style custard-based ice cream containing egg yolks.
- Frozen yoghurt – which may contain lactic acid organisms or simply yoghurt flavours.
- Milk ice – similar to ice cream, but unaerated and containing less dairy fat.
- Sorbet – fruit-based, aerated, sugar syrup that contains neither fat nor milk.
- Sherbet – similar to a sorbet, but containing some milk or cream.
- Water ice – frozen sugar syrup with flavours and colours, such as an "ice lolly" or "popsicle".
- Fruit ice – similar to water ice, but made with real fruit juice.

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What these all have in common is that they are sweetened, flavoured, contain ice and, unlike any other frozen food, are normally eaten in the frozen state.

The legal definition of ice cream varies from country to country. The UK follows the EUROGLACES Code for Edible Ices,[1] an industry code that defines standards to facilitate a common understanding of the various types of edible ices marketed across the European Union. "Ice cream" is defined as a frozen food product that is an emulsion typically composed of water and/or milk, edible fats, proteins and sugars. "Dairy ice cream" must contain at least 5% dairy fat and must contain no fats other than milk fat, with the exception of fat that is present in another ingredient – for example, egg, flavouring or emulsifier. In the USA, ice cream must contain at least 10% milk fat and 20% total milk solids and must weigh a minimum of 0.54 kg per litre.[2]

Ice cream is often categorized as premium, standard or economy. Premium ice cream is generally made from the best-quality ingredients and has a relatively high amount of dairy fat and a low amount of air (hence it is relatively expensive), whereas economy ice cream is made from cheaper ingredients (*e.g.* vegetable fats) and contains more air. However, these terms have no legal standing within the UK market and one manufacturer's economy ice cream may be similar to a standard ice cream from another.

Most people are very familiar with the appearance, taste and texture of ice cream and there are many recipes in cookery books for making it. However, few people know *why* certain ingredients and a time-consuming preparation process are required. The answer is that ice cream is an extremely complex, intricate and delicate substance. In fact, it has been called "just about the most complex food colloid of all".[3] The science of ice cream consists of understanding its ingredients, processing, microstructure and texture and, crucially, the links between them. This requires a whole range of scientific disciplines, including physical chemistry, food science, colloid science, chemical engineering, microscopy, materials science and consumer science, as shown in Figure 1.1.

The ingredients and processing create the microstructure shown schematically in Figure 1.2. It consists of ice crystals, air bubbles and fat droplets in the size range from 1 μm to 0.1 mm

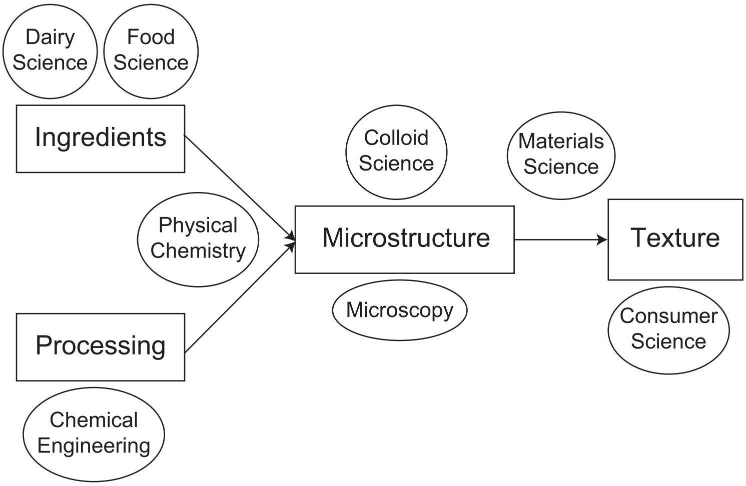

Figure 1.1 The sciences of ice cream.

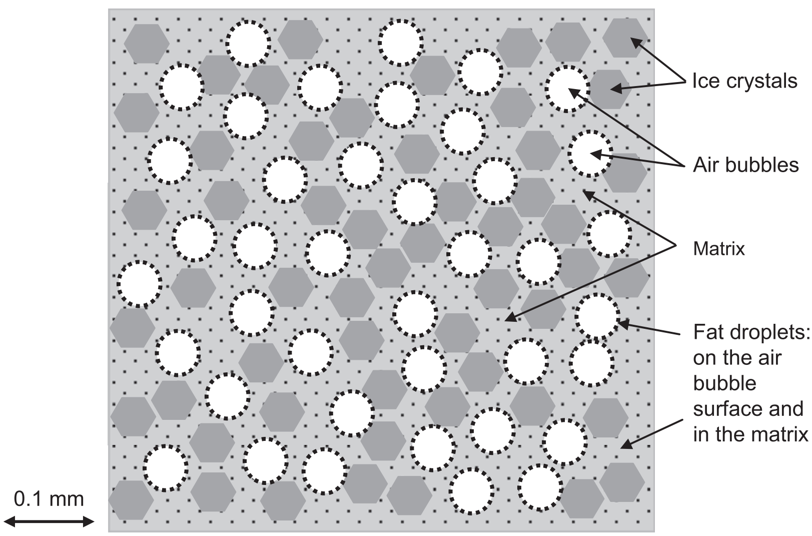

Figure 1.2 Schematic diagram of the microstructure of ice cream.

and a viscous solution of sugars, polysaccharides and milk proteins, known as the matrix. The texture we perceive when we eat ice cream is the sensory manifestation of the microstructure. Thus the microstructure is at the heart of the science of ice cream and forms the central theme running through this book.

In order to describe the science of ice cream, it is first necessary to describe some of the physical chemistry and colloid science that underpin it; these are laid out in Chapter 2. Chapters 3 and 4 cover the ingredients and the ice cream making process, respectively. Chapter 5 focuses on the production of various types of ice cream product. The physical and sensory measurements used to quantify and describe ice cream are discussed in Chapter 6 and the microstructure, as well as its relationship with the texture, is examined in Chapter 7. Chapter 8 discusses some specific types of ice cream that have become of increasing importance in recent years, such as low-fat, low-sugar and non-dairy (plant-based) ice creams. Chapter 9 describes a number of experiments that illustrate the science of ice cream, which may be performed in the laboratory, classroom or kitchen. We begin, however, by looking at where and when ice cream was invented, and how it has evolved into the huge range of products eaten by billions of people all around the world today.

1.2 THE HISTORY OF ICE CREAM

Ice cream as we recognize it today has been in existence for at least 300 years, although its origins probably go much further back in time. The history of ice cream is full of myths and stories, which have little real evidence to support them. A typical "history" begins with the Roman Emperor Nero (AD 37–68), who is said to have eaten fruit chilled with snow brought down from the mountains by slaves. Elsewhere, Mongolian horsemen are reputed to have invented ice cream. They took cream in containers made from animal intestines as provisions on long journeys across the Gobi desert in winter. As they galloped, the cream was vigorously shaken, while the sub-zero temperatures simultaneously caused it to freeze. The expansion of the Mongol empire spread this idea through China, from where Marco Polo reputedly brought the idea to Italy when he returned from his travels in 1295. It has been claimed that ice cream was introduced to France from Italy when the 14-year-old Catherine de Medici was married to the Duc d'Orléans (later Henri II of France) in 1533. Her entourage included Italian chefs who brought the recipe for ice cream with them. The secret of making ice cream remained known to only a few. So precious was it that Charles I of England is said to have offered his French chef a pension of £500 per year to keep his recipe secret.

However, historical research has found little factual evidence to support any of these stories. The only mention of ice in connection with Nero comes from Pliny the Elder in the first century AD, who records the discovery that water that has been boiled freezes faster and is healthier. There is no mention of ice cream in any of the manuscripts describing Marco Polo's travels. Indeed, modern historians doubt that he even reached China. It is unlikely that Catherine's chefs knew how to make ice cream because, at that time, the method of refrigeration by mixing ice and salt was known in Europe to only a handful of scientists. Nor is there any documentary evidence of Charles I's chef.

We cannot be absolutely sure of exactly who invented ice cream, or where and when. In reality, the history of ice cream is closely associated with the development of refrigeration techniques and can be traced in several stages coupled with these:

(1) Cooling food and drink by mixing it with snow or ice.
(2) The discovery that dissolving salts in water produces cooling.
(3) The discovery (and spread of the knowledge) that mixing salts and snow or ice cools it even further.
(4) The invention of the ice cream maker in the mid-19th century.
(5) The development of mechanical refrigeration in the late 19th and early 20th centuries.

Concurrent with these developments, a vast range of recipes has been developed, spanning the spectrum from chilled fruit juices to what we understand as ice cream today. The evolution of ice cream has been described in detail in the two excellent histories listed under Further Reading and the following summary owes much to their research.

Ice has been used to chill food and drink for at least 4000 years in many different parts of the world. Ice cellars dating back to 2000 BC have been discovered in Mesopotamia (present day Iraq). Records from the Zhou dynasty in China in about the 11th century BC describe the role of the court iceman, who had a large staff responsible for harvesting ice every winter and storing it in cellars to be served with drinks in the summer. An ice-cooled dessert, made from water buffaloes' milk mixed with flour and camphor, is recorded in the Tang dynasty (AD 618–907). In Greece, drinks were served with snow in about 500 BC and a Roman cookery book dating from the 1st century AD includes recipes for sweet desserts that are sprinkled with snow before serving. Sweet drinks cooled with ice are recorded in Persia in the 2nd century AD. Rather than harvesting ice during the winter, the Persians exploited the cold desert nights to freeze water that had been placed in shallow pits.

The first significant step forward was the discovery that water is cooled when salts – such as common salt (sodium chloride), saltpetre (potassium nitrate), sal-ammoniac (ammonium chloride) or alum (a mixture of aluminium sulphate and potassium sulphate) – are dissolved in it. When the crystals dissolve, the strong bonds between the ions are broken, extracting heat from the surrounding water, so the temperature drops. Adding a mixture of five parts ammonium chloride and five parts potassium nitrate to 16 parts water at 10 °C causes the temperature of the mixture to drop to about −12 °C, sufficient to freeze a vessel of pure water immersed in it. This phenomenon was first recorded in an Indian poem from the 4th century AD and described in detail in an Arabic medical textbook from 1242. Another book in Arabic containing sorbet recipes appeared at about the same time.

These methods were known in the West by the early 16th century. Soon thereafter, in 1589, Giambattista Della Porta, a scientist from Naples, made the breakthrough that paved the way for making ice cream as we know it today. He reported the discovery, possibly based on Arabic knowledge of cooling techniques, that much greater cooling could be achieved by mixing ice and salt. (This effect is explained in Chapter 2.) Della Porta used this discovery to freeze wine in a glass placed in a mixture of ice and salt. Others became aware of the phenomenon and the first reports of iced desserts produced using this method of freezing began to appear in the 1620s. These appear to have been water ices, rather than ice cream. Water ices were served at banquets in Paris, Naples, Florence and Spain during the 1660s.

The earliest evidence for ice cream in England comes from a list of the food that was served at the feast of St George at Windsor in May 1671; ice cream was served, but only at King Charles II's table. Techniques and recipes then developed, notably in France. In 1674, Nicholas Lemery published a recipe for water ice and, two years later, Pierre Barra described freezing a mixture of fruit, cream and sugar using snow and saltpetre. L. Audiger noted the importance of whipping the mixture during freezing to break up large ice crystals in 1692. This technique still forms the basis of ice cream making today.

More recipe books appeared in the 18th century that helped to widen knowledge of how to make water ices and ice creams, which became a luxury served by the aristocracy at banquets. This was accompanied by the production of special moulds, ice pails (for keeping ices cold) and serving cups. The extent of the spread of ice cream can be seen by the orders for the utensils associated with its production and serving. Those who are recorded as having such services include Louis XV of France, Gustaf III of Sweden and Catherine the Great of Russia. Ice cream remained the preserve of royalty and aristocracy in Europe and of high-ranking officials in the USA, where, in 1744, the Governor of Maryland was one of the first people recorded to have served it. A presidential connection with ice cream began with George Washington, who often served it at official functions, as did the third president, Thomas Jefferson. After his time as American envoy in France, Jefferson brought back an ice cream recipe from his French chef. Ice cream was served at the inaugural dinner for the fourth president, James Madison, and subsequently became a regular feature of the White House menu.

By the beginning of the 19th century, ice cream had started to move from the tables of the aristocracy into restaurants and cafes that served the well-off middle classes. This was accompanied by an increasing interest in good food, reflected in the appearance of many books on cooking. Ice cream was made by hand, by placing a bowl containing the ice cream mix in a barrel filled with ice and salt and using a scraper to remove the growing ice crystals from the sides of the bowl. This practice continued until the 1840s, when Nancy Johnson of Philadelphia invented the first ice cream making machine. Her invention consisted of two spatulas that fitted tightly into a long cylindrical barrel. The spatulas contained holes and were attached to a shaft that could be rotated with a crank. The outside of the cylinder was cooled with a mixture of salt and ice. The holes made it easier to rotate the spatulas in the mix and simultaneously scrape ice crystals off the inner wall of the cylinder. This invention simplified ice cream production and ensured a more uniform texture than had previously been possible.

At about the same time, people in Europe were coming up with other ideas for ice cream making machines and a large number of patents were published, both in Europe and the USA, in the following decades. Mechanization meant that ice cream could be produced more cheaply and in much larger volumes. Jacob Fussell, a dairy farmer from Baltimore, USA, is commonly considered to be the founder of the modern ice cream industry. Faced with a surplus of milk during the summer, he decided to sell it as ice cream. He built the first ice cream factory in 1851 and subsequently expanded to Washington, Boston and New York, where he sold ice cream at a price that ordinary people could afford.

In England, ice cream became available to the masses towards the end of the 19th century. This was due, in part, to the emigration of Italians, many of whom became ice cream vendors in cities around the world. Of the approximately ten thousand Italians living in England and Wales at the time of the 1890 census, just under one thousand listed their occupation as street vendors, most of whom sold ice cream. They sold it in small, thick-walled glasses, known as "penny-licks". These were usually wiped with a cloth and re-used, and were thus a considerable health hazard, particularly for children. The street vendors would drum up business by calling out "ecco un poco", Italian for "here is a little". The words "ecco un poco" became "hokey pokey", now meaning either poor quality ice cream or deception/trickery.[4] Poor hygiene standards necessitated the introduction of regulations around the turn of the century.

One person who was not impressed with the quality of street-sold ice cream was Agnes Marshall (1855–1905). She was a celebrity cook with an interest in new technology. As well as inventing an ice cream maker (Figure 1.3), she wrote several books, including two dedicated to ice cream. She toured extensively, lecturing and demonstrating her techniques to large audiences, and campaigned for better standards of food hygiene. She can also claim to have invented the ice cream cone in 1888, since a recipe for "cornets with cream" appears in one of her books. However, the cone really took off at the 1904 St Louis World's Fair, when a stall selling ice cream ran out of dishes in which to serve it. Ernest A. Hamwi, a waffle vendor on the

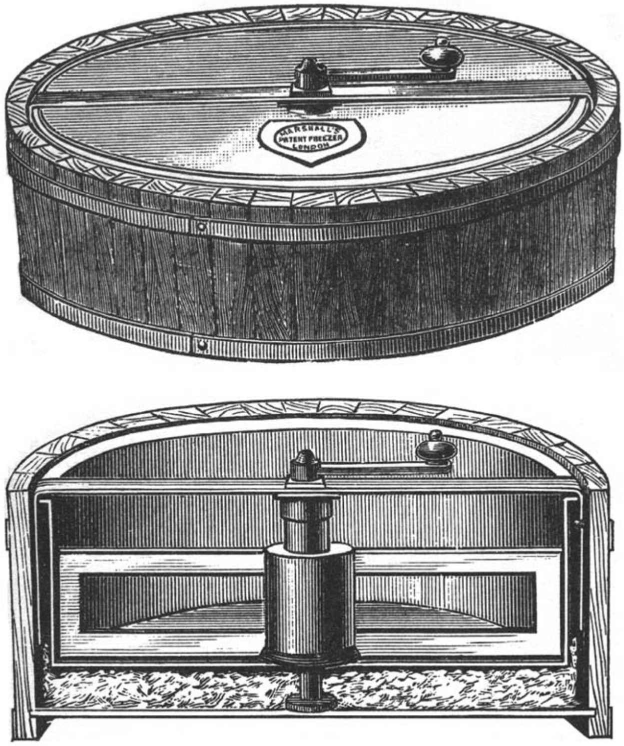

Figure 1.3 Mrs Marshall's ice cream maker (courtesy of the London Canal Museum, www.canalmuseum.org.uk).

next-door stall, had the bright idea of rolling up his waffles as cones instead. There were tens of thousands of visitors at the Fair, so the idea then spread rapidly throughout the USA.

Ice cream making requires a source of ice. Starting in the first half of the 19th century, ice was collected from rivers and lakes in Norway, Sweden, Canada and the northern USA and then shipped to cities in Europe, the USA and even as far away as Calcutta! However, physicists and engineers were developing techniques for artificial refrigeration based on the liquefaction of gases such as propane and ammonia. The gas is compressed until it liquefies, during which process it heats up. It is then allowed to cool down to near ambient temperature while still pressurized. The pressure is then released, which allows the liquid to expand and evaporate, extracting heat from the surroundings in the process, hence providing refrigeration (Experiment 1 in Chapter 9 demonstrates this principle). A number of cooling machines were invented, but Carl von Linde's invention, demonstrated at the 1873 World's Fair in Vienna, was the first really successful one. Using ammonia gas in a closed circuit, he could rapidly produce substantial quantities of ice. Artificial production eventually took over from harvesting as the main source of ice.

In the first few decades of the 20th century, ice cream production expanded and became industrialized. The major reason for this was technological developments in the production and transport of ice cream. The development of mechanical refrigeration allowed the use of chilled brine (a concentrated salt solution that freezes well below 0 °C) as the refrigerant instead of salt and ice. This greatly increased the rate of heat transfer between the ice cream mix and the refrigerant, and hence the speed of production. In 1927, Clarence Vogt invented the continuous freezer, with a horizontal (rather than a vertical) cylinder. The mix was pumped in at one end and ice cream pumped out from the other, so that ice cream could be made continuously, rather than in batches. The modern ice cream factory freezer had arrived. (Note the distinction between the freezer in the factory, which converts ice cream mix into frozen ice cream, and the domestic or shop freezer in which you keep it cold before consumption. Throughout this book, the term "factory freezer" is used for the former and "freezer" for the latter.) These developments were accompanied by the introduction of pasteurization, which reduced concerns over the safety of ice cream, and homogenization, which produced a smoother, creamier product by breaking the fat into tiny droplets. Better transport through the railways and road networks made the supply of ingredients and the distribution of products possible over much greater distances than before.

Many of the names that are familiar to consumers around the world today have their origins in this period. In the USA, Breyers, which had consisted of a number of shops in the 1870s, built new factories and expanded its annual production of ice cream to nearly four million litres by 1914. In the UK, Wall's set up its first ice cream factory in Acton, London in 1922. Ice cream was sold from tricycles and the phrase "Stop me and buy one" became very familiar to ice cream consumers. Production came to a halt during the Second World War due to shortages of ingredients and the need to convert the factories to producing essential foods, such as margarine. When production resumed after the war, rationing was still in place and it was forbidden to use cream to make ice cream. Manufacturers therefore switched to using vegetable fats and milk powder. By the time rationing ended in 1953, the British public had become accustomed to the taste of ice cream produced with vegetable fats. For this reason, and also because it is cheaper, a substantial amount of ice cream in the UK is still made with vegetable fats today. Partly as a result of a shortage of labour after the war, the main sales outlet changed from tricycles to freezers in corner shops.

As their businesses grew, large companies such as Wall's, which became part of Unilever in 1929, and Lyons Maid, which was bought by Nestlé in 1992, set up research and development departments to study ice cream and its manufacture. One of the scientists who conducted research for Lyons in the 1950s was a young chemist, Margaret Roberts, who later became better known under her married name of Thatcher. In recent years, many other companies have joined the long-established manufacturers. Two of the best known of these are Häagen-Dazs and Ben & Jerry's. Reuben Mattus founded Häagen-Dazs in New York in 1960. He chose the (meaningless) name because it sounded Danish and was therefore associated with dairy produce. This fitted well with his new product, a high-quality, high-price ice cream. Ben Cohen and Jerry Greenfield set up an ice cream parlour in an abandoned petrol station in Burlington, Vermont in 1978. Their all-natural ice cream company with a strong social mission became famous after winning a major court battle with Häagen-Dazs (owned at the time by Pillsbury). Ben & Jerry's was acquired by Unilever in 2000 and has become a globally recognized brand.

1.3 THE GLOBAL ICE CREAM MARKET

Ice cream is made and eaten in almost every country in the world. The total worldwide production of ice cream and related frozen desserts was nearly 20 billion litres in 2022, *i.e.* an average of 2.5 litres per person, worth over $50 billion (retail value in USD).[5] Unilever and Nestlé are the largest producers worldwide, with about one-third of the market between them. The largest brands by retail value are Magnum, followed by Häagen-Dazs.

A huge range of different flavours is available, including savoury ones. Differences in culture and climate produce wide variations in the amounts, types and flavours of ice cream produced and consumed in different countries.

The USA is the largest producer of ice cream (about 4.4 billion litres per annum). It has a per capita annual consumption of about 13 litres, most of which is purchased in supermarkets and consumed at home, often as a snack (much as biscuits are eaten in the UK). The countries with the highest per capita consumption are Australia (21 litres) and New Zealand (15 litres). Much of this is sold in scoop shops, restaurants and retail outlets and is eaten out of the home, although new routes to the consumer (*e.g.* through e-commerce) have grown significantly over the last few years. Premium ice cream makes up a large part of the market, although low-fat ice cream, non-dairy ice cream, frozen yoghurt and sherbet account for smaller, but significant, portions. Sales of plant-based ice cream have grown by over 10% year-on-year since 2011. Globally, vanilla is the most popular flavour, accounting for about a quarter of sales, followed by chocolate. Ice cream with pieces of other components (known as inclusions), such as cookie dough, marshmallows, fruit chunks, nuts, chocolate, toffee or fudge, is becoming increasingly popular.

The European per capita ice cream consumption figures were, until recent years, rather surprising at first sight, because less ice cream was consumed in hot southern European countries (such as Spain and Portugal) than in cold northern European countries (such as Sweden, Norway and Germany). The main reason for this was that northern Europeans have historically consumed lots of milk, cheese and butter, whereas the southern European diet has traditionally contained much less dairy produce. Another factor that influences consumption is whether households own a large freezer in which to keep quantities of ice cream. This, in turn, may be influenced by local building regulations. However, in the last decade, the gap in consumption between northern and southern European countries has reduced significantly. In Spain, Portugal and Italy, the consumption is about 10 litres per capita, similar to that of Sweden and not much less than in Norway and Finland (about 12 and 13 litres per capita, respectively).

The UK falls roughly in the middle of the list of European countries, with a per capita consumption of about 8 litres and an annual retail sales value of about £2 billion. A small number of large companies, such as Wall's (Unilever), R&R Ice Cream and General Mills UK have substantial market shares, but about half is taken by several hundred small independent companies. These mostly employ fewer than ten people and only sell locally. The most popular flavours in the UK are vanilla, chocolate and strawberry and, like in the USA, ice cream often contains inclusions to provide greater interest and variety for the consumer. Magnum, Ben & Jerry's and Häagen-Dazs constitute the largest ice cream brands in the UK measured by retail value.

The market is very different in other parts of the world. For example, in Southeast Asia, the largest demand is for refreshing products, such as water ices. As well as the familiar ones, ice cream also comes in flavours that may seem strange and exotic to Western palates – for example, green tea and red bean ice cream in Japan, sweet corn ice cream in Malaysia, chilli ice cream in Indonesia and sesame seed ice cream in Korea.

1.4 SELLING ICE CREAM: FUN, INDULGENCE AND REFRESHMENT

Two factors that have a major effect on the sales of ice cream products are the weather and advertising. Ice cream sales are very seasonal, peaking in the summer months. The weather can have a substantial impact on sales, especially at particular times, such as bank holiday weekends. Although this is beyond anyone's control, the large companies try to increase their sales by spending several million pounds each year on promoting their products. Ice cream advertisements have typically been based on one of three themes: fun, indulgence or refreshment. A fun image is typically used to promote products aimed at children or families. The advertising for premium products usually aims to project an indulgent image, either through the experience of eating the product as a whole (sometimes using an element of sexual attraction) or by highlighting the use of premium quality ingredients. Water ice products – for example, ice lollies – are frequently marketed based on images of fun and/or their ability to cool down and refresh the consumer. Whether a product is indulgent or refreshing largely depends on its ingredients and the processing method by which it is produced. We will look at these in Chapters 3–5.

In recent years, ice cream marketing has moved beyond the traditional aspects of fun, indulgence and refreshment. The provenance, quality or sustainable sourcing of the ingredients and the nature of the packaging (*e.g.* the materials used and its recyclability) are often highlighted in marketing communications. Some ice cream brands have sought to identify with particular values that resonate with consumers, such as protection of the environment and social justice. Other brands focus on providing ice creams that fit the dietary lifestyles of consumers – for example, vegan, ketogenic or high protein.

Advertising channels have also evolved significantly over the last decade. In the past, they were weighted towards television commercials and in-store promotions, but they now include online advertising *via* brand websites and through social media platforms such as Instagram or Facebook. Social media platforms allow ice cream brands to both advertise and interact with consumers and also provide a public way for consumers to give their feedback on the quality of their products.

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