ON FOOD AND COOKING

The Science and Lore of the Kitchen

COMPLETELY REVISED AND UPDATED

Harold McGee

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To my family

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ACKNOWLEDGMENTS

Along with many food writers today, I feel a great debt of gratitude to Alan Davidson for the way he brought new substance, scope, and playfulness to our subject. On top of that, it was Alan who informed me that I would have to revise *On Food and Cooking*—before I'd even held the first copy in my hands! At our first meeting in 1984, over lunch, he asked me what the book had to say about fish. I told him that I mentioned fish in passing as one form of animal muscle and thus of meat. And so this great fish enthusiast and renowned authority on the creatures of several seas gently suggested that, in view of the fact that fish are diverse creatures and their flesh very unlike meat, they really deserve special and extended attention. Well, yes, they really do. There are many reasons for wishing that this revision hadn't taken as long as it did, and one of the biggest is the fact that I can't show Alan the new chapter on fish. I'll always be grateful to Alan and to Jane for their encouragement and advice, and for the years of friendship which began with that lunch. This book and my life would have been much poorer without them.

I would also have liked to give this book to Nicholas Kurti—bracing myself for the discussion to come! Nicholas wrote a heartwarmingly positive review of the first edition in *Nature,* then followed it up with a Sunday-afternoon visit and an extended interrogation based on the pages of questions that he had accumulated as he wrote the review. Nicholas's energy, curiosity, and enthusiasm for good food and the telling "little experiment" were infectious, and animated the early Erice workshops. They and he are much missed.

Coming closer to home and the present, I thank my family for the affection and patient optimism that have kept me going day after day: son John and daughter Florence, who have lived with this book and experimental dinners for more than half their years, and enlivened both with their gusto and strong opinions; my father, Chuck McGee, and mother, Louise Hammersmith; brother Michael and sisters Ann and Joan; and Chuck Hammersmith, Werner Kurz, Richard Thomas, and Florence Jean and Harold Long. Throughout these last few trying years, my wife Sharon Long has been constantly caring and supportive. I'm deeply grateful to her for that gift.

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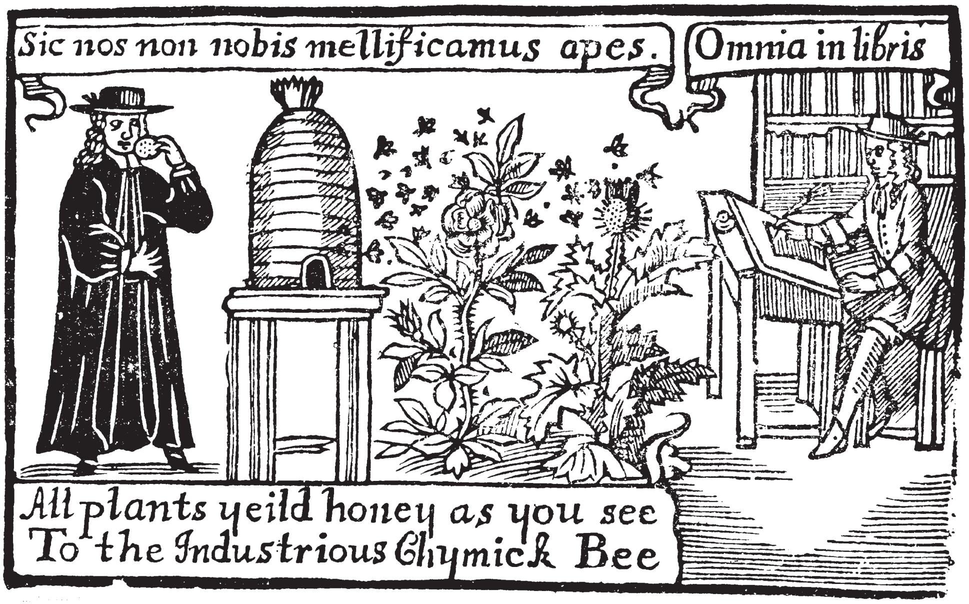
ON FOOD AND COOKING



The everyday alchemy of creating food for the body and the mind. This 17th-century woodcut compares the alchemical ("chymick") work of the bee and the scholar, who transform nature's raw materials into honey and knowledge. Whenever we cook we become practical chemists, drawing on the accumulated knowledge of generations, and transforming what the Earth offers us into more concentrated forms of pleasure and nourishment. (The first Latin caption reads "Thus we bees make honey, not for ourselves"; the second, "All things in books," the library being the scholar's hive. Woodcut from the collection of the International Bee Research Association.)

INTRODUCTION

Cooking and Science, 1984 and 2004

This is the revised and expanded second edition of a book that I first published in 1984, twenty long years ago. In 1984, canola oil and the computer mouse and compact discs were all novelties. So was the idea of inviting cooks to explore the biological and chemical insides of foods. It was a time when a book like this really needed an introduction!

Twenty years ago the worlds of science and cooking were neatly compartmentalized. There were the basic sciences, physics and chemistry and biology, delving deep into the nature of matter and life. There was food science, an applied science mainly concerned with understanding the materials and processes of industrial manufacturing. And there was the world of small-scale home and restaurant cooking, traditional crafts that had never attracted much scientific attention. Nor did they really need any. Cooks had been developing their own body of practical knowledge for thousands of years, and had plenty of reliable recipes to work with.

I had been fascinated by chemistry and physics when I was growing up, experimented with electroplating and Tesla coils and telescopes, and went to Caltech planning to study astronomy. It wasn't until after I'd changed directions and moved on to English literature—and had begun to cook—that I first heard of food science. At dinner one evening in 1976 or 1977, a friend from New Orleans wondered aloud why dried beans were such a problematic food, why indulging in red beans and rice had to cost a few hours of sometimes embarrassing discomfort. Interesting question! A few days later, working in the library and needing a break from 19th-century poetry, I remembered it and the answer a biologist friend had dug up (indigestible sugars), thought I would browse in some food books, wandered over to that section, and found shelf after shelf of strange titles. *Journal of Food Science. Poultry Science. Cereal Chemistry.* I flipped through a few volumes, and among the mostly bewildering pages found hints of answers to other questions that had never occurred to me. Why do eggs solidify when we cook them? Why do fruits turn brown when we cut them? Why is bread dough bouncily alive, and why does bounciness make good bread? Which kinds of dried beans are the worst offenders, and how can a cook tame them? It was great fun to make and share these little discoveries, and I began to think that many people interested in food might enjoy them. Eventually I found time to immerse myself in food science and history and write *On Food and Cooking: The Science and Lore of the Kitchen.*

As I finished, I realized that cooks more serious than my friends and I might be skeptical about the relevance of cells and molecules to their craft. So I spent much of the introduction trying to bolster my case. I began by quoting an unlikely trio of authorities, Plato, Samuel Johnson, and Jean Anthelme Brillat-Savarin, all of whom suggested that cooking deserves detailed and serious study. I pointed out that a 19th-century German chemist still influences how many people think about cooking meat, and that around the turn of the 20th century, Fannie Farmer began her cookbook with what she called "condensed scientific knowledge" about ingredients. I noted a couple of errors in modern cookbooks by Madeleine Kamman and Julia Child, who were ahead of their time in taking chemistry seriously. And I proposed that science can make cooking more interesting by connecting it with the basic workings of the natural world.

A lot has changed in twenty years! It turned out that *On Food and Cooking* was riding a rising wave of general interest in food, a wave that grew and grew, and knocked down the barriers between science and cooking, especially in the last decade. Science has found its way into the kitchen, and cooking into laboratories and factories.

In 2004 food lovers can find the science of cooking just about everywhere. Magazines and newspaper food sections devote regular columns to it, and there are now a number of books that explore it, with Shirley Corriher's 1997 *CookWise* remaining unmatched in the way it integrates explanation and recipes. Today many writers go into the technical details of their subjects, especially such intricate things as pastry, chocolate, coffee, beer, and wine. Kitchen science has been the subject of television series aired in the United States, Canada, the United Kingdom, and France. And a number of food molecules and microbes have become familiar figures in the news, both good and bad. Anyone who follows the latest in health and nutrition knows about the benefits of antioxidants and phytoestrogens, the hazards of trans fatty acids, acrylamide, *E. coli* bacteria, and mad cow disease.

Professional cooks have also come to appreciate the value of the scientific approach to their craft. In the first few years after *On Food and Cooking* appeared, many young cooks told me of their frustration in trying to find out *why* dishes were prepared a certain way, or why ingredients behave as they do. To their traditionally trained chefs and teachers, understanding food was less important than mastering the tried and true techniques for preparing it. Today it's clearer that curiosity and understanding make their own contribution to mastery. A number of culinary schools now offer "experimental" courses that investigate the whys of cooking and encourage critical thinking. And several highly regarded chefs, most famously Ferran Adrià in Spain and Heston Blumenthal in England, experiment with industrial and laboratory tools—gelling agents from seaweeds and bacteria, non-sweet sugars, aroma extracts, pressurized gases, liquid nitrogen—to bring new forms of pleasure to the table.

As science has gradually percolated into the world of cooking, cooking has been drawn into academic and industrial science. One effective and charming force behind this movement was Nicholas Kurti, a physicist and food lover at the University of Oxford, who lamented in 1969: "I think it is a sad reflection on our civilization that while we can and do measure the temperature in the atmosphere of Venus, we do not know what goes on inside our soufflés." In 1992, at the age of 84, Nicholas nudged civilization along by organizing an International Workshop on Molecular and Physical Gastronomy at Erice, Sicily, where for the first time professional cooks, basic scientists from universities, and food scientists from industry worked together to advance gastronomy, the making and appreciation of foods of the highest quality.

The Erice meeting continues, renamed the "International Workshop on Molecular Gastronomy 'N. Kurti' " in memory of its founder. And over the last decade its focus, the understanding of culinary excellence, has taken on new economic significance. The modern industrial drive to maximize efficiency and minimize costs generally lowered the quality and distinctiveness of food products: they taste much the same, and not very good. Improvements in quality can now mean a competitive advantage; and cooks have always been the world's experts in the applied science of deliciousness. Today, the French National Institute of Agricultural Research sponsors a group in Molecular Gastronomy at the Collège de France (its leader, Hervé This, directs the Erice workshop); chemist Thorvald Pedersen is the inaugural Professor of Molecular Gastronomy at Denmark's Royal Veterinary and Agricultural University; and in the United States, the rapidly growing membership of the Research Chefs Association specializes in bringing the chef's skills and standards to the food industry.

So in 2004 there's no longer any need to explain the premise of this book. Instead, there's more for the book itself to explain! Twenty years ago, there wasn't much demand for information about extra-virgin olive oil or balsamic vinegar, farmed salmon or grass-fed beef, cappuccino or white tea, Sichuan pepper or Mexican mole, sake or well-tempered chocolate. Today there's interest in all these and much more. And so this second edition of *On Food and Cooking* is substantially longer than the first. I've expanded the text by two thirds in order to cover a broader range of ingredients and preparations, and to explore them in greater depth. To make room for new information about foods, I've dropped the separate chapters on human physiology, nutrition, and additives. Of the few sections that survive in similar form from the first edition, practically all have been rewritten to reflect fresh information, or my own fresh understanding.

This edition gives new emphasis to two particular aspects of food. The first is the diversity of ingredients and the ways in which they're prepared. These days the easy movement of products and people makes it possible for us to taste foods from all over the world. And traveling back in time through old cookbooks can turn up forgotten but intriguing ideas. I've tried throughout to give at least a brief indication of the range of possibilities offered by foods themselves and by different national traditions.

The other new emphasis is on the flavors of foods, and sometimes on the particular molecules that create flavor. Flavors are something like chemical chords, composite sensations built up from notes provided by different molecules, some of which are found in many foods. I give the chemical names of flavor molecules when I think that being specific can help us notice flavor relationships and echoes. The names may seem strange and intimidating at first, but they're just names and they'll become more familiar. Of course people have made and enjoyed well seasoned dishes for thousands of years with no knowledge of molecules. But a dash of flavor chemistry can help us make fuller use of our senses of taste and smell, and experience more—and find more pleasure—in what we cook and eat.

Now a few words about the scientific approach to food and cooking and the organization of this book. Like everything on earth, foods are mixtures of different chemicals, and the qualities that we aim to influence in the kitchen—taste, aroma, texture, color, nutritiousness—are all manifestations of chemical properties. Nearly two hundred years ago, the eminent gastronome Jean Anthelme Brillat-Savarin lectured his cook on this point, tongue partly in cheek, in *The Physiology of Taste*:

> You are a little opinionated, and I have had some trouble in making you understand that the phenomena which take place in your laboratory are nothing other than the execution of the eternal laws of nature, and that certain things which you do without thinking, and only because you have seen others do them, derive nonetheless from the highest scientific principles.

The great virtue of the cook's time-tested, thought-less recipes is that they free us from the distraction of having to guess or experiment or analyze as we prepare a meal. On the other hand, the great virtue of thought and analysis is that they free us from the necessity of following recipes, and help us deal with the unexpected, including the inspiration to try something new. Thoughtful cooking means paying attention to what our senses tell us as we prepare it, connecting that information with past experience and with an understanding of what's happening to the food's inner substance, and adjusting the preparation accordingly.

To understand what's happening within a food as we cook it, we need to be familiar with the world of invisibly small molecules and their reactions with each other. That idea may seem daunting. There are a hundred-plus chemical elements, many more combinations of those elements into molecules, and several different forces that rule their behavior. But scientists always simplify reality in order to understand it, and we can do the same. Foods are mostly built out of just four kinds of molecules—water, proteins, carbohydrates, and fats. And their behavior can be pretty well described with a few simple principles. If you know that heat is a manifestation of the movements of molecules, and that sufficiently energetic collisions disrupt the structures of molecules and eventually break them apart, then you're very close to understanding why heat solidifies eggs and makes foods tastier.

Most readers today have at least a vague idea of proteins and fats, molecules and energy, and a vague idea is enough to follow most of the explanations in the first 13 chapters, which cover common foods and ways of preparing them. Chapters 14 and 15 then describe in some detail the molecules and basic chemical processes involved in all cooking; and the Appendix gives a brief refresher course in the basic vocabulary of science. You can refer to these final sections occasionally, to clarify the meaning of pH or protein coagulation as you're reading about cheese or meat or bread, or else read through them on their own to get a general introduction to the science of cooking.

Finally, a request. In this book I've sifted through and synthesized a great deal of information, and have tried hard to double-check both facts and my interpretations of them. I'm greatly indebted to the many scientists, historians, linguists, culinary professionals, and food lovers on whose learning I've been able to draw. I will also appreciate the help of readers who notice errors that I've made and missed, and who let me know so that I can correct them. My thanks in advance.

As I finish this revision and think about the endless work of correcting and perfecting, my mind returns to the first Erice workshop and a saying shared by Jean-Pierre Philippe, a chef from Les Mesnuls, near Versailles. The subject of the moment was egg foams. Chef Philippe told us that he had thought he knew everything there was to know about meringues, until one day a phone call distracted him and he left his mixer running for half an hour. Thanks to the excellent result and to other surprises throughout his career, he said, *Je sais, je sais que je sais jamais:* "I know, I know that I never know." Food is an infinitely rich subject, and there's always something about it to understand better, something new to discover, a fresh source of interest, ideas, and delight.

A Note About Units of Measurement, and About the Drawings of Molecules

Throughout this book, temperatures are given in both degrees Fahrenheit (ºF), the standard units in the United States, and degrees Celsius or Centigrade (ºC), the units used by most other countries. The Fahrenheit temperatures shown in several charts can be converted to Celsius by using the formula ºC = (ºF−32) x 0.56. Volumes and weights are given in both U.S. kitchen units—teaspoons, quarts, pounds—and metric units—milliliters, liters, grams, and kilograms. Lengths are generally given in millimeters (mm); 1 mm is about the diameter of the degree symbol º. Very small lengths are given in microns (µ). One micron is 1 micrometer, or 1 thousandth of a millimeter.

Single molecules are so small, a tiny fraction of a micron, that they can seem abstract, hard to imagine. But they are real and concrete, and have particular structures that determine how they—and the foods made out of them—behave in the kitchen. The better we can visualize what they're like and what happens to them, the easier it is to understand what happens in cooking. And in cooking it's generally a molecule's overall shape that matters, not the precise placement of each atom. In most of the drawings of molecules in this book, only the overall shapes are shown, and they're represented in different ways—as long thin lines, long thick lines, honeycomb-like rings with some atoms indicated by letters—depending on what behavior needs to be explained. Many food molecules are built from a backbone of interconnected carbon atoms, with a few other kinds of atoms (mainly hydrogen and oxygen) projecting from the backbone. The carbon backbone is what creates the overall structure, so often it is drawn with no indications of the atoms themselves, just lines that show the bonds between atoms.

CHAPTER 1

MILK AND DAIRY PRODUCTS

What better subject for the first chapter than the food with which we all begin our lives? Humans are mammals, a word that means "creatures of the breast," and the first food that any mammal tastes is milk. Milk is food for the beginning eater, a gulpable essence distilled by the mother from her own more variable and challenging diet. When our ancestors took up dairying, they adopted the cow, the ewe, and the goat as surrogate mothers. These creatures accomplish the miracle of turning meadow and hay into buckets of human nourishment. And their milk turned out to be an elemental fluid rich in possibility, just a step or two away from luxurious cream, fragrant golden butter, and a multitude of flavorful foods concocted by friendly microbes.

No wonder that milk captured the imaginations of many cultures. The ancient Indo-Europeans were cattle herders who moved out from the Caucasian steppes to settle vast areas of Eurasia around 3000 BCE; and milk and butter are prominent in the creation myths of their descendents, from India to Scandinavia. Peoples of the Mediterranean and Middle East relied on the oil of their olive tree rather than butter, but milk and cheese still figure in the Old Testament as symbols of abundance and creation.

The modern imagination holds a very different view of milk! Mass production turned it and its products from precious, marvelous resources into ordinary commodities, and medical science stigmatized them for their fat content. Fortunately a more balanced view of dietary fat is developing; and traditional versions of dairy foods survive. It's still possible to savor the remarkable foods that millennia of human ingenuity have teased from milk. A sip of milk itself or a scoop of ice cream can be a Proustian draft of youth's innocence and energy and possibility, while a morsel of fine cheese is a rich meditation on maturity, the fulfillment of possibility, the way of all flesh.

MAMMALS AND MILK

The Evolution of Milk

How and why did such a thing as milk ever come to be? It came along with warm-bloodedness, hair, and skin glands, all of which distinguish mammals from reptiles. Milk may have begun around 300 million years ago as a protective and nourishing skin secretion for hatchlings being incubated on their mother's skin, as is true for the platypus today. Once it evolved, milk contributed to the success of the mammalian family. It gives newborn animals the advantage of ideally formulated food from the mother even after birth, and therefore the opportunity to continue their physical development outside the womb. The human species has taken full advantage of this opportunity: we are completely helpless for months after birth, while our brains finish growing to a size that would be difficult to accommodate in the womb and birth canal. In this sense, milk helped make possible the evolution of our large brain, and so helped make us the unusual animals we are.

Milk and Butter: Primal Fluids

When the gods performed the sacrifice, with the first Man as the offering, spring was the melted butter, summer the fuel, autumn the offering. They anointed that Man, born at the beginning, as a sacrifice on the straw. . . . From that full sacrifice they gathered the grains of butter, and made it into the creatures of the air, the forest, and the village . . . cattle were born from it, and sheep and goats were born from it.

—The *Rg Veda,* Book 10, ca. 1200 BCE

. . . I am come down to deliver [my people] out of the hands of the Egyptians, and to bring them up out of that land unto a good land and a large, unto a land flowing with milk and honey. . . .

—God to Moses on Mount Horeb (Exodus 3:8)

Hast thou not poured me out as milk, and curdled me like cheese?

—Job to God (Job 10:10)

The Rise of the Ruminants

All mammals produce milk for their young, but only a closely related handful have been exploited by humans. Cattle, water buffalo, sheep, goats, camels, yaks: these suppliers of plenty were created by a scarcity of food. Around 30 million years ago, the earth's warm, moist climate became seasonally arid. This shift favored plants that could grow quickly and produce seeds to survive the dry period, and caused a great expansion of grasslands, which in the dry seasons became a sea of desiccated, fibrous stalks and leaves. So began the gradual decline of the horses and the expansion of the deer family, the *ruminants,* which evolved the ability to survive on dry grass. Cattle, sheep, goats, and their relatives are all ruminants.

The key to the rise of the ruminants is their highly specialized, multichamber stomach, which accounts for a fifth of their body weight and houses trillions of fiber-digesting microbes, most of them in the first chamber, or *rumen*. Their unique plumbing, together with the habit of regurgitating and rechewing partly digested food, allows ruminants to extract nourishment from high-fiber, poor-quality plant material. Ruminants produce milk copiously on feed that is otherwise useless to humans and that can be stockpiled as hay or silage. Without them there would be no dairying.

Dairy Animals of the World

Only a small handful of animal species contributes significantly to the world's milk supply.

The Cow, European and Indian The immediate ancestor of *Bos taurus,* the common dairy cow, was *Bos primigenius,* the long-horned wild aurochs. This massive animal, standing 6 ft/180 cm at the shoulder and with horns 6.5 in/17 cm in diameter, roamed Asia, Europe, and North Africa in the form of two overlapping races: a humpless European-African form, and a humped central Asian form, the zebu. The European race was domesticated in the Middle East around 8000 BCE, the heat- and parasite-tolerant zebu in south-central Asia around the same time, and an African variant of the European race in the Sahara, probably somewhat later.

In its principal homeland, central and south India, the zebu has been valued as much for its muscle power as its milk, and remains rangy and long-horned. The European dairy cow has been highly selected for milk production at least since 3000 BCE, when confinement to stalls in urban Mesopotamia and poor winter feed led to a reduction in body and horn size. To this day, the prized dairy breeds—Jerseys, Guernseys, Brown Swiss, Holsteins—are short-horned cattle that put their energy into making milk rather than muscle and bone. The modern zebu is not as copious a producer as the European breeds, but its milk is 25% richer in butterfat.

The Buffalo The water buffalo is relatively unfamiliar in the West but the most important bovine in tropical Asia. *Bubalus bubalis* was domesticated as a draft animal in Mesopotamia around 3000 BCE, then taken to the Indus civilizations of present-day Pakistan, and eventually through India and China. This tropical animal is sensitive to heat (it wallows in water to cool down), so it proved adaptable to milder climates. The Arabs brought buffalo to the Middle East around 700 CE, and in the Middle Ages they were introduced throughout Europe. The most notable vestige of that introduction is a population approaching 100,000 in the Campagna region south of Rome, which supplies the milk for true mozzarella cheese, *mozzarella di bufala*. Buffalo milk is much richer than cow's milk, so mozzarella and Indian milk dishes are very different when the traditional buffalo milk is replaced with cow's milk.

The Yak The third important dairy bovine is the yak, *Bos grunniens*. This long-haired, bushy-tailed cousin of the common cow is beautifully adapted to the thin, cold, dry air and sparse vegetation of the Tibetan plateau and mountains of central Asia. It was domesticated around the same time as lowland cattle. Yak milk is substantially richer in fat and protein than cow milk. Tibetans in particular make elaborate use of yak butter and various fermented products.

The Goat The goat and sheep belong to the "ovicaprid" branch of the ruminant family, smaller animals that are especially at home in mountainous country. The goat, *Capra hircus,* comes from a denizen of the mountains and semidesert regions of central Asia, and was probably the first animal after the dog to be domesticated, between 8000 and 9000 BCE in present-day Iran and Iraq. It is the hardiest of the Eurasian dairy animals, and will browse just about any sort of vegetation, including woody scrub. Its omnivorous nature, small size, and good yield of distinctively flavored milk—the highest of any dairy animal for its body weight—have made it a versatile milk and meat animal in marginal agricultural areas.

The Sheep The sheep, *Ovis aries,* was domesticated in the same region and period as its close cousin the goat, and came to be valued and bred for meat, milk, wool, and fat. Sheep were originally grazers on grassy foothills and are somewhat more fastidious than goats, but less so than cattle. Sheep's milk is as rich as the buffalo's in fat, and even richer in protein; it has long been valued in the Eastern Mediterranean for making yogurt and feta cheese, and elsewhere in Europe for such cheeses as Roquefort and pecorino.

The Camel The camel family is fairly far removed from both the bovids and ovicaprids, and may have developed the habit of rumination independently during its early evolution in North America. Camels are well adapted to arid climates, and were domesticated around 2500 BCE in central Asia, primarily as pack animals. Their milk, which is roughly comparable to cow's milk, is collected in many countries, and in northeast Africa is a staple food.

The Origins of Dairying

When and why did humans extend our biological heritage as milk drinkers to the cultural practice of drinking the milk of *other* animals? Archaeological evidence suggests that sheep and goats were domesticated in the grasslands and open forest of present-day Iran and Iraq between 8000 and 9000 BCE, a thousand years before the far larger, fiercer cattle. At first these animals would have been kept for meat and skins, but the discovery of milking was a significant advance. Dairy animals could produce the nutritional equivalent of a slaughtered meat animal or more each year for several years, and in manageable daily increments. Dairying is the most efficient means of obtaining nourishment from uncultivated land, and may have been especially important as farming communities spread outward from Southwest Asia.

Small ruminants and then cattle were almost surely first milked into containers fashioned from skins or animal stomachs. The earliest hard evidence of dairying to date consists of clay sieves, which have been found in the settlements of the earliest northern European farmers, from around 5000 BCE. Rock drawings of milking scenes were made a thousand years later in the Sahara, and what appear to be the remains of cheese have been found in Egyptian tombs of 2300 BCE.

Diverse Traditions

Early shepherds would have discovered the major transformations of milk in their first containers. When milk is left to stand, fat-enriched cream naturally forms at the top, and if agitated, the cream becomes butter. The remaining milk naturally turns acid and curdles into thick yogurt, which draining separates into solid curd and liquid whey. Salting the fresh curd produces a simple, long-keeping cheese. As dairyers became more adept and harvested greater quantities of milk, they found new ways to concentrate and preserve its nourishment, and developed distinctive dairy products in the different climatic regions of the Old World.

In arid southwest Asia, goat and sheep milk was lightly fermented into yogurt that could be kept for several days, sun-dried, or kept under oil; or curdled into cheese that could be eaten fresh or preserved by drying or brining. Lacking the settled life that makes it possible to brew beer from grain or wine from grapes, the nomadic Tartars even fermented mare's milk into lightly alcoholic *koumiss,* which Marco Polo described as having "the qualities and flavor of white wine." In the high country of Mongolia and Tibet, cow, camel, and yak milk was churned to butter for use as a high-energy staple food.

In semitropical India, most zebu and buffalo milk was allowed to sour overnight into a yogurt, then churned to yield buttermilk and butter, which when clarified into *ghee* (p. 37) would keep for months. Some milk was repeatedly boiled to keep it sweet, and then preserved not with salt, but by the combination of sugar and long, dehydrating cooking (see box, p. 26).

The Mediterranean world of Greece and Rome used economical olive oil rather than butter, but esteemed cheese. The Roman Pliny praised cheeses from distant provinces that are now parts of France and Switzerland. And indeed cheese making reached its zenith in continental and northern Europe, thanks to abundant pastureland ideal for cattle, and a temperate climate that allowed long, gradual fermentations.

The one major region of the Old World not to embrace dairying was China, perhaps because Chinese agriculture began where the natural vegetation runs to often toxic relatives of wormwood and epazote rather than ruminant-friendly grasses. Even so, frequent contact with central Asian nomads introduced a variety of dairy products to China, whose elite long enjoyed yogurt, koumiss, butter, acid-set curds, and, around 1300 and thanks to the Mongols, even milk in their tea!

Dairying was unknown in the New World. On his second voyage in 1493, Columbus brought sheep, goats, and the first of the Spanish longhorn cattle that would proliferate in Mexico and Texas.

Milk in Europe and America: From Farmhouse to Factory

Preindustrial Europe In Europe, dairying took hold on land that supported abundant pasturage but was less suited to the cultivation of wheat and other grains: wet Dutch lowlands, the heavy soils of western France and its high, rocky central massif, the cool, moist British Isles and Scandinavia, alpine valleys in Switzerland and Austria. With time, livestock were selected for the climate and needs of different regions, and diversified into hundreds of distinctive local breeds (the rugged Brown Swiss cow for cheesemaking in the mountains, the diminutive Jersey and Guernsey for making butter in the Channel Islands). Summer milk was preserved in equally distinctive local cheeses. By medieval times, fame had come to French Roquefort and Brie, Swiss Appenzeller, and Italian Parmesan. In the Renaissance, the Low Countries were renowned for their butter and exported their productive Friesian cattle throughout Europe.

Until industrial times, dairying was done on the farm, and in many countries mainly by women, who milked the animals in early morning and after noon and then worked for hours to churn butter or make cheese. Country people could enjoy good fresh milk, but in the cities, with confined cattle fed inadequately on spent brewers' grain, most people saw only watered-down, adulterated, contaminated milk hauled in open containers through the streets. Tainted milk was a major cause of child mortality in early Victorian times.

Industrial and Scientific Innovations Beginning around 1830, industrialization transformed European and American dairying. The railroads made it possible to get fresh country milk to the cities, where rising urban populations and incomes fueled demand, and new laws regulated milk quality. Steam-powered farm machinery meant that cattle could be bred and raised for milk production alone, not for a compromise between milk and hauling, so milk production boomed, and more than ever was drunk fresh. With the invention of machines for milking, cream separation, and churning, dairying gradually moved out the hands of milkmaids and off the farms, which increasingly supplied milk to factories for mass production of cream, butter, and cheese.

From the end of the 19th century, chemical and biological innovations have helped make dairy products at once more hygienic, more predictable, and more uniform. The great French chemist Louis Pasteur inspired two fundamental changes in dairy practice: *pasteurization,* the pathogen-killing heat treatment that bears his name; and the use of standard, purified microbial cultures to make cheeses and other fermented foods. Most traditional cattle breeds have been abandoned in favor of high-yielding black-and-white Friesian (Holstein) cows, which now account for 90% of all American dairy cattle and 85% of British. The cows are farmed in ever larger herds and fed an optimized diet that seldom includes fresh pasturage, so most modern milk lacks the color, flavor, and seasonal variation of preindustrial milk.

Dairy Products Today Today dairying is split into several big businesses with nothing of the dairymaid left about them. Butter and cheese, once prized, delicate concentrates of milk's goodness, have become inexpensive, mass-produced, uninspiring commodities piling up in government warehouses. Manufacturers now remove much of what makes milk, cheese, ice cream, and butter distinctive and pleasurable: they remove milk fat, which suddenly became undesirable when medical scientists found that saturated milk fat tends to raise blood cholesterol levels and can contribute to heart disease. Happily the last few years have brought a correction in the view of saturated fat, a reaction to the juggernaut of mass production, and a resurgent interest in full-flavored dairy products crafted on a small scale from traditional breeds that graze seasonally on green pastures.

MILK AND HEALTH

Milk has long been synonymous with wholesome, fundamental nutrition, and for good reason: unlike most of our foods, it is actually designed to be a food. As the sole sustaining food of the calf at the beginning of its life, it's a rich source of many essen-

Food Words: *Milk* and *Dairy*

In their roots, both *milk* and *dairy* recall the physical effort it once took to obtain milk and transform it by hand. *Milk* comes from an Indo-European root that meant both "milk" and "to rub off," the connection perhaps being the stroking necessary to squeeze milk from the teat. In medieval times, *dairy* was originally *dey-ery,* meaning the room in which the *dey,* or woman servant, made milk into butter and cheese. *Dey* in turn came from a root meaning "to knead bread" (*lady* shares this root)—perhaps a reflection not only of the servant's several duties, but also of the kneading required to squeeze buttermilk out of butter (p. 34) and sometimes the whey out of cheese.

tial body-building nutrients, particularly protein, sugars and fat, vitamin A, the B vitamins, and calcium.

Over the last few decades, however, the idealized portrait of milk has become more shaded. We've learned that the balance of nutrients in cow's milk doesn't meet the needs of human infants, that most adult humans on the planet can't digest the milk sugar called lactose, that the best route to calcium balance may not be massive milk intake. These complications help remind us that milk was designed to be a food for the young and rapidly growing calf, not for the young or mature human.

Milk Nutrients

Nearly all milks contain the same battery of nutrients, the relative proportions of which vary greatly from species to species. Generally, animals that grow rapidly are fed with milk high in protein and minerals. A calf doubles its weight at birth in 50 days, a human infant in 100; sure enough, cow's milk contains more than double the protein and minerals of mother's milk. Of the major nutrients, ruminant milk is seriously lacking only in iron and in vitamin C. Thanks to the rumen microbes, which convert the unsaturated fatty acids of grass and grain into saturated fatty acids, the milk fat of ruminant animals is the most highly saturated of our common foods. Only coconut oil beats it. Saturated fat does raise blood cholesterol levels, and high blood cholesterol is associated with an increased risk of heart disease; but the other foods in a balanced diet can compensate for this disadvantage (p. 253).

The box below shows the nutrient contents of both familiar and unfamiliar milks. These figures are only a rough guide, as the breakdown by breed indicates; there's also much variation from animal to animal, and in a given animal's milk as its lactation period progresses.

The Compositions of Various Milks

The figures in the following table are the percent of the milk's weight accounted for by its major components.

Milk	Fat	Protein	Lactose	Minerals	Water
Human	4.0	1.1	6.8	0.2	88
Cow	3.7	3.4	4.8	0.7	87
Holstein/Friesian	3.6	3.4	4.9	0.7	87
Brown Swiss	4.0	3.6	4.7	0.7	87
Jersey	5.2	3.9	4.9	0.7	85
Zebu	4.7	3.3	4.9	0.7	86
Buffalo	6.9	3.8	5.1	0.8	83
Yak	6.5	5.8	4.6	0.8	82
Goat	4.0	3.4	4.5	0.8	88
Sheep	7.5	6.0	4.8	1.0	80
Camel	2.9	3.9	5.4	0.8	87
Reindeer	17	11	2.8	1.5	68
Horse	1.2	2.0	6.3	0.3	90
Fin whale	42	12	1.3	1.4	43

Milk in Infancy and Childhood: Nutrition and Allergies

In the middle of the 20th century, when nutrition was thought to be a simple matter of protein, calories, vitamins, and minerals, cow's milk seemed a good substitute for mother's milk: more than half of all six-month-olds in the United States drank it. Now that figure is down to less than 10%. Physicians now recommend that plain cow's milk not be fed to children younger than one year. One reason is that it provides too much protein, and not enough iron and highly unsaturated fats, for the human infant's needs. (Carefully prepared formula milks are better approximations of breast milk.) Another disadvantage to the early use of cow's milk is that it can trigger an allergy. The infant's digestive system is not fully formed, and can allow some food protein and protein fragments to pass directly into the blood. These foreign molecules then provoke a defensive response from the immune system, and that response is strengthened each time the infant eats. Somewhere between 1% and 10% of American infants suffer from an allergy to the abundant protein in cow's milk, whose symptoms may range from mild discomfort to intestinal damage to shock. Most children eventually grow out of milk allergy.

Milk after Infancy: Dealing with Lactose

In the animal world, humans are exceptional for consuming milk of any kind after they have started eating solid food. And people who drink milk after infancy are the exception within the human species. The obstacle is the milk sugar lactose, which can't be absorbed and used by the body as is: it must first be broken down into its component sugars by digestive enzymes in the small intestine. The lactose-digesting enzyme, *lactase,* reaches its maximum levels in the human intestinal lining shortly after birth, and then slowly declines, with a steady minimum level commencing at between two and five years of age and continuing through adulthood.

The logic of this trend is obvious: it's a waste of its resources for the body to produce an enzyme when it's no longer needed; and once most mammals are weaned, they never encounter lactose in their food again. But if an adult without much lactase activity does ingest a substantial amount of milk, then the lactose passes through the small intestine and reaches the large intestine, where bacteria metabolize it, and in the process produce carbon dioxide, hydrogen, and methane: all discomforting gases. Sugar also draws water from the intestinal walls, and this causes a bloated feeling or diarrhea.

Low lactase activity and its symptoms are called *lactose intolerance.* It turns out that adult lactose intolerance is the rule rather than the exception: lactose-tolerant adults are a distinct minority on the planet. Several thousand years ago, peoples in northern Europe and a few other regions underwent a genetic change that allowed them to produce lactase throughout life, probably because milk was an exceptionally important resource in colder climates. About 98% of Scandinavians are lactose-tolerant, 90% of French and Germans, but only 40% of southern Europeans and North Africans, and 30% of African Americans.

Coping with Lactose Intolerance Fortunately, lactose intolerance is not the same as milk intolerance. Lactase-less adults can consume about a cup/250 ml of milk per day without severe symptoms, and even more of other dairy products. Cheese contains little or no lactose (most of it is drawn off in the whey, and what little remains in the curd is fermented by bacteria and molds). The bacteria in yogurt generate lactose-digesting enzymes that remain active in the human small intestine and work for us there. And lactose-intolerant milk fans can now buy the lactose-digesting enzyme itself in liquid form (it's manufactured from a fungus, *Aspergillus*), and add a few drops to any dairy product just before they consume it.

New Questions about Milk

Milk has been especially valued for two nutritional characteristics: its richness in calcium, and both the quantity and quality of its protein. Recent research has raised some fascinating questions about each of these.

Perplexity about Calcium and Osteoporosis Our bones are constructed from two primary materials: proteins, which form a kind of scaffolding, and calcium phosphate, which acts as a hard, mineralized, strengthening filler. Bone tissue is constantly being deconstructed and rebuilt throughout our adult lives, so healthy bones require adequate protein and calcium supplies from our diet. Many women in industrialized countries lose so much bone mass after menopause that they're at high risk for serious fractures. Dietary calcium clearly helps prevent this potentially dangerous loss, or *osteoporosis.* Milk and dairy products are the major source of calcium in dairying countries, and U.S. government panels have recommended that adults consume the equivalent of a quart (liter) of milk daily to prevent osteoporosis.

This recommendation represents an extraordinary concentration of a single food, and an unnatural one—remember that the ability to drink milk in adulthood, and the habit of doing so, is an aberration limited to people of northern European descent. A quart of milk supplies two-thirds of a day's recommended protein, and would displace from the diet other foods—vegetables, fruits, grains, meats, and fish—that provide their own important nutritional benefits. And there clearly must be other ways of maintaining healthy bones. Other countries, including China and

The Many Influences on Bone Health

Good bone health results from a proper balance between the two ongoing processes of bone deconstruction and reconstruction. These processes depend not only on calcium levels in the body, but also on physical activity that stimulates bone-building; hormones and other controlling signals; trace nutrients (including vitamin C, magnesium, potassium, and zinc); and other as yet unidentified substances. There appear to be factors in tea and in onions and parsley that slow bone deconstruction significantly. Vitamin D is essential for the efficient absorption of calcium from our foods, and also influences bone building. It's added to milk, and other sources include eggs, fish and shellfish, and our own skin, where ultraviolet light from the sun activates a precursor molecule.

The amount of calcium we have available for bone building is importantly affected by how much we excrete in our urine. The more we lose, the more we have to take in from our foods. Various aspects of modern eating increase calcium excretion and so boost our calcium requirement. A high intake of salt is one, and another is a high intake of animal protein, the metabolism of whose sulfur-containing amino acids acidifies our urine, and pulls neutralizing calcium salts from bone.

The best insurance against osteoporosis appears to be frequent exercise of the bones that we want to keep strong, and a well-rounded diet that is rich in vitamins and minerals, moderate in salt and meat, and includes a variety of calcium-containing foods. Milk is certainly a valuable one, but so are dried beans, nuts, corn tortillas and tofu (both processed with calcium salts), and several greens—kale, collards, mustard greens.

Japan, suffer much lower fracture rates than the United States and milk-loving Scandinavia, despite the fact that their people drink little or no milk. So it seems prudent to investigate the many other factors that influence bone strength, especially those that slow the deconstruction process (see box, p. 15). The best answer is likely to be not a single large white bullet, but the familiar balanced diet and regular exercise.

Milk Proteins Become Something More We used to think that one of the major proteins in milk, casein (p. 19), was mainly a nutritional reservoir of amino acids with which the infant builds its own body. But this protein now appears to be a complex, subtle orchestrator of the infant's metabolism. When it's digested, its long amino-acid chains are first broken down into smaller fragments, or peptides. It turns out that many hormones and drugs are also peptides, and a number of casein peptides do affect the body in hormone-like ways. One reduces breathing and heart rates, another triggers insulin release into the blood, and a third stimulates the scavenging activity of white blood cells. Do the peptides from cow's milk affect the metabolism of human children or adults in significant ways? We don't yet know.

MILK BIOLOGY AND CHEMISTRY

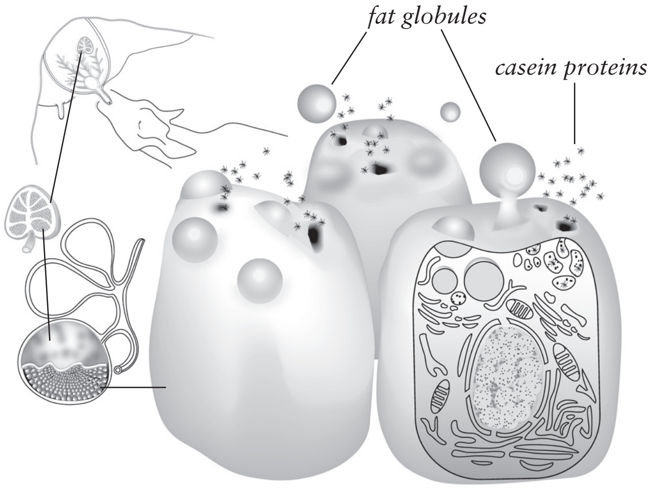
How the Cow Makes Milk

Milk is food for the newborn, and so dairy animals must give birth before they will produce significant quantities of milk. The mammary glands are activated by changes in the balance of hormones toward the end of pregnancy, and are stimulated to continue secreting milk by regular removal of milk from the gland. The optimum sequence for milk production is to breed the cow again 90 days after it calves, milk it for 10 months, and let it go dry for the two months before the next calving. In intensive operations, cows aren't allowed to waste energy on grazing in variable pastures; they're given hay or silage (whole corn or other plants, partly dried and then preserved by fermentation in airtight silos) in confined lots, and are milked only during their two or three most productive years. The combination of breeding and optimal feed formulation has led to per-animal yields of a hundred pounds or 15 gallons/58 liters per day, though the American average is about half that. Dairy breeds of sheep and goats give about one gallon per day.

The first fluid secreted by the mammary gland is colostrum, a creamy, yellow solution of concentrated fat, vitamins, and proteins, especially immunoglobulins and antibodies. After a few days, when the colostrum flow has ceased and the milk is saleable, the calf is put on a diet of reconstituted and soy milks, and the cow is milked two or three times daily to keep the secretory cells working at full capacity.

The Milk Factory The mammary gland is an astonishing biological factory, with many different cells and structures working together to create, store, and dispense milk. Some components of milk come directly from the cow's blood and collect in the udder. The principal nutrients, however—fats, sugar, and proteins—are assembled by the gland's secretory cells, and then released into the udder.

A Living Fluid Milk's blank appearance belies its tremendous complexity and vitality. It's alive in the sense that, fresh from the udder, it contains living white blood cells, some mammary-gland cells, and various bacteria; and it teems with active enzymes, some floating free, some embedded in the membranes of the fat globules. Pasteurization (p. 22) greatly reduces this vitality; in fact residual enzyme activity is taken as a sign that the heat treatment was insufficient. Pasteurized milk contains very few living cells or active enzyme molecules, so it is more predictably free of bacteria that could cause food poisoning, and more sta-



The making of milk. Cells in the cow's mammary gland synthesize the components of milk, including proteins and globules of milk fat, and release them into many thousands of small compartments that drain toward the teat. The fat globules pass through the cells' outer membranes, and carry parts of the cell membrane on their surface.

ble; it develops off-flavors more slowly than raw milk. But the dynamism of raw milk is prized in traditional cheese making, where it contributes to the ripening process and deepens flavor.

Milk owes its milky opalescence to microscopic fat globules and protein bundles, which are just large enough to deflect light rays as they pass through the liquid. Dissolved salts and milk sugar, vitamins, other proteins, and traces of many other compounds also swim in the water that accounts for the bulk of the fluid. The sugar, fat, and proteins are by far the most important components, and we'll look at them in detail in a moment.

First a few words about the remaining components. Milk is slightly acidic, with a pH between 6.5 and 6.7, and both acidity and salt concentrations strongly affect the behavior of the proteins, as we'll see. The fat globules carry colorless vitamin A and its yellow-orange precursors the carotenes, which are found in green feed and give milk and undyed butter whatever color they have. Breeds differ in the amount of carotene they convert into vitamin A; Guernsey and Jersey cows convert little and give especially golden milk, while at the other extreme sheep, goats, and water buffalo process nearly all of their carotene, so their milk and butter are nutritious but white. Riboflavin, which has a greenish color, can sometimes be seen in skim milk or in the watery translucent whey that drains from the curdled proteins of yogurt.

Milk Sugar: Lactose

The only carbohydrate found in any quantity in milk is also peculiar to milk (and a handful of plants), and so was named *lactose,* or "milk sugar." (*Lact-* is a prefix based on the Greek word for "milk"; we'll encounter it again in the names of milk proteins, acids, and bacteria.) Lactose is a composite of the two simple sugars glucose and galactose, which are joined together in the secretory cell of the mammary gland, and nowhere else in the animal body. It provides nearly half of the calories in human milk, and 40% in cow's milk, and gives milk its sweet taste.

The uniqueness of lactose has two major practical consequences. First, we need a special enzyme to digest lactose; and many adults lack that enzyme and have to be careful about what dairy products they consume (p. 14). Second, most microbes take some time to make their own lactose-digesting enzyme before they can grow well in milk, but one group has enzymes at the ready and can get a head start on all the others. The bacteria known as *Lactobacilli* and *Lactococci* not only grow on lactose immediately, they also convert it into lactic acid ("milk acid"). They thus acidify the milk, and in so doing, make it less habitable by other microbes, including many that would make the milk unpalatable or cause disease. Lactose and the lactic-acid bacteria therefore turn milk sour, but help prevent it from spoiling, or becoming undrinkable.

Lactose is one-fifth as sweet as table sugar, and only one-tenth as soluble in water (200 vs. 2,000 gm/l), so lactose crystals readily form in such products as condensed milk and ice cream and can give them a sandy texture.

Milk Fat

Milk fat accounts for much of the body, nutritional value, and economic value of milk. The milk-fat globules carry the fat-soluble vitamins (A, D, E, K), and about half the calories of whole milk. The higher the fat content of milk, the more cream or butter can be made from it, and so the higher the price it will bring. Most cows secrete more fat in winter, due mainly to concentrated winter feed and the approaching end of their lactation period. Certain breeds, notably Guernseys and Jerseys from the Channel Islands between Britain and France, produce especially rich milk and large fat globules. Sheep and buffalo milks contain up to twice the butterfat of whole cow's milk (p. 13).

The way the fat is packaged into globules accounts for much of milk's behavior in the kitchen. The membrane that surrounds each fat globule is made up of phospholipids (fatty acid emulsifiers, p. 802) and proteins, and plays two major roles. It separates the droplets of fat from each other and prevents them from pooling together into one large mass; and it protects the fat molecules from fat-digesting enzymes in the milk that would otherwise attack them and break them down into rancid-smelling and bitter fatty acids.

Creaming When milk fresh from the udder is allowed to stand and cool for some hours, many of its fat globules rise and form a fat-rich layer at the top of the container. This phenomenon is called *creaming*, and for millennia it was the natural first step toward obtaining fat-enriched cream and butter from milk. In the 19th century, centrifuges were developed to concentrate the fat globules more rapidly and thoroughly, and homogenization was invented to prevent whole milk from separating in this way (p. 23). The globules rise because their fat is lighter than water, but they rise much faster than their buoyancy alone can account for. It turns out that a number of minor milk proteins attach themselves loosely to the fat globules and knit together clusters of about a million globules that have a stronger lift than single globules do. Heat denatures these proteins and prevents the globule clustering, so that the fat globules in unhomogenized but pasteurized milk rise more slowly into a shallower, less distinct layer. Because of their small globules and low clustering activity, the milks of goats, sheep, and water buffalo are very slow to separate.

Milk Fat Globules Tolerate Heat . . . Interactions between fat globules and milk proteins are also responsible for the remarkable tolerance of milk and cream to heat. Milk and cream can be boiled and reduced for hours, until they're nearly dry, without breaching the globule membranes enough to release their fat. The globule membranes are robust to begin with, and it turns out that heating unfolds many of the milk proteins and makes them more prone to stick to the globule surface and to each other—so the globule armor actually gets progressively thicker as heating proceeds. Without this stability to heat, it would be impossible to make many cream-enriched sauces and reduced-milk sauces and sweets.

. . . But Are Sensitive to Cold Freezing is a different story. It is fatal to the fat globule membrane. Cold milk fat and freezing water both form large, solid, jagged crystals that pierce, crush, and rend the thin veil of phospholipids and proteins around the globule, just a few molecules thick. If you freeze milk or cream and then thaw it, much of the membrane material ends up floating free in the liquid, and many of the fat globules get stuck to each other in grains of butter. Make the mistake of heating thawed milk or cream, and the butter grains melt into puddles of oil.

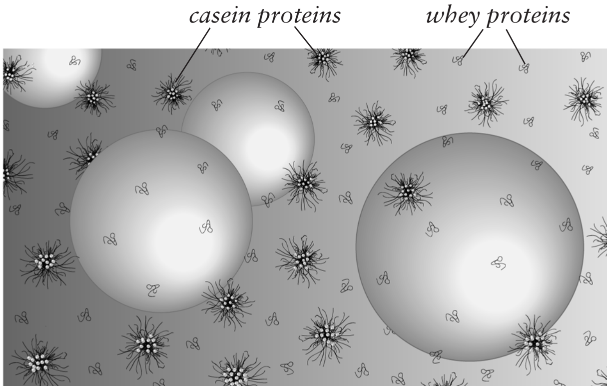
Milk Proteins: Coagulation by Acid and Enzymes

Two Protein Classes: Curd and Whey There are dozens of different proteins floating around in milk. When it comes to cooking behavior, fortunately, we can reduce the protein population to two basic groups: Little Miss Muffet's curds and whey. The two groups are distinguished by their reaction to acids. The handful of curd proteins, the *caseins,* clump together in acid conditions and form a solid mass, or *coagulate,* while all the rest, the whey proteins, remain suspended in the liquid. It's the clumping nature of the caseins that makes possible most thickened milk products, from yogurt to cheese. The whey proteins play a more minor role; they influence the texture of casein curds, and stabilize the milk foams on specialty coffees. The caseins usually outweigh the whey proteins, as they do in cow's milk by 4 to 1.

Both caseins and whey proteins are unusual among food proteins in being largely tolerant of heat. Where cooking coagulates the proteins in eggs and meat into solid masses, it does not coagulate the proteins in milk and cream—unless the milk or cream has become acidic. Fresh milk and cream can be boiled down to a fraction of their volume without curdling.

The Caseins The casein family includes four different kinds of proteins that gather together into microscopic family units called *micelles.* Each casein micelle contains a few thousand individual protein molecules, and measures about a ten-thousandth of a millimeter across, about one-fiftieth the size of a fat globule. Around a tenth of the volume of milk is taken up by casein micelles. Much of the calcium in milk is in the micelles, where it acts as a kind of glue holding the protein molecules together. One portion of calcium binds individual protein molecules together into small clusters of 15 to 25. Another portion then helps pull several hundred of the clusters together to form the micelle (which is also held together by the water-avoiding hydrophobic portions of the proteins bonding to each other).

Keeping Micelles Separate . . . One member of the casein family is especially influential in these gatherings. That is kappa-casein, which caps the micelles once they reach a



A close-up view of milk. Fat globules are suspended in a fluid made up of water, individual molecules of whey protein, bundles of casein protein molecules, and dissolved sugars and minerals.

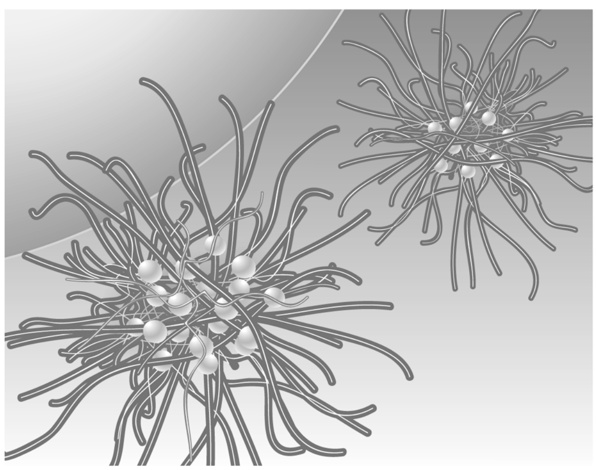
certain size, prevents them from growing larger, and keeps them dispersed and separate. One end of the capping-casein molecule extends from the micelle out into the surrounding liquid, and forms a "hairy layer" with a negative electrical charge that repels other micelles.

. . . And Knitting Them Together in Curds The intricate structure of casein micelles can be disturbed in several ways that cause the micelles to flock together and the milk to curdle. One way is souring. Milk's normal pH is about 6.5, or just slightly acidic. If it gets acid enough to approach pH 5.5, the capping-casein's negative charge is neutralized, the micelles no longer repel each other, and they therefore gather in loose clusters. At the same acidity, the calcium glue that holds the micelles together dissolves, the micelles begin to fall apart, and their individual proteins scatter. Beginning around pH 4.7, the scattered casein proteins lose their negative charge, bond to each other again and form a continuous, fine network: and the milk solidifies, or curdles. This is what happens when milk gets old and sour, or when it's intentionally cultured with acid-producing bacteria to make yogurt or sour cream.

Another way to cause the caseins to curdle is the basis of cheese making. Chymosin, a digestive enzyme from the stomach of a milk-fed calf, is exquisitely designed to give the casein micelles a haircut (p. 57). It clips off just the part of the capping-casein that extends into the surrounding liquid and shields the micelles from each other. Shorn of their hairy layer, the micelles all clump together—without the milk being noticeably sour.

The Whey Proteins Subtract the four caseins from the milk proteins, and the remainder, numbering in the dozens, are the whey proteins. Where the caseins are mainly nutritive, supplying amino acids and calcium for the calf, the whey proteins include defensive proteins, molecules that bind to and transport other nutrients, and enzymes. The most abundant one by far is lactoglobulin, whose biological function remains a mystery. It's a highly structured protein that is readily denatured by cooking. It unfolds at 172ºF/78ºC, when its sulfur atoms are exposed to the surrounding liquid and react with hydrogen ions to form hydrogen sulfide gas, whose powerful aroma contributes to the characteristic flavor of cooked milk (and many other animal foods).

In boiling milk, unfolded lactoglobulin binds not to itself but to the capping-casein



A model of the milk protein casein, which occurs in micelles, or small bundles a fraction of the size of a fat globule. A single micelle consists of many individual protein molecules (lines) *held together by particles of calcium phosphate* (small spheres).

on the casein micelles, which remain separate; so denatured lactoglobulin doesn't coagulate. When denatured in acid conditions with relatively little casein around, as in cheese whey, lactoglobulin molecules do bind to each other and coagulate into little clots, which can be made into whey cheeses like true ricotta. Heat-denatured whey proteins are better than their native forms at stabilizing air bubbles in milk foams and ice crystals in ice creams; this is why milks and creams are usually cooked for these preparations (pp. 26, 43).

Milk Flavor

The flavor of fresh milk is balanced and subtle. It's distinctly sweet from the lactose, slightly salty from its complement of minerals, and very slightly acid. Its mild, pleasant aroma is due in large measure to short-chain fatty acids (including butyric and capric acids), which help keep highly saturated milk fat fluid at body temperature, and which are small enough that they can evaporate into the air and reach our nose. Normally, free fatty acids give an undesirable, soapy flavor to foods. But in sparing quantities, the 4- to 12-carbon rumen fatty acids, branched versions of these, and acid-alcohol combinations called esters, provide milk with its fundamental blend of animal and fruity notes. The distinctive smells of goat and sheep milks are due to two particular branched 8-carbon fatty acids (4-ethyl-octanoic, 4-methyl-octanoic) that are absent in cow's milk. Buffalo milk, from which traditional mozzarella cheese is made, has a characteristic blend of modified fatty acids reminiscent of mushrooms and freshly cut grass, together with a barnyardy nitrogen compound (indole).

The basic flavor of fresh milk is affected by the animals' feed. Dry hay and silage are relatively poor in fat and protein and produce a less complicated, mildly cheesy aroma, while lush pasturage provides raw material for sweet, raspberry-like notes (derivatives of unsaturated long-chain fatty acids), as well as barnyardy indoles.

Flavors from Cooking Low-temperature pasteurization (p. 22) slightly modifies milk flavor by driving off some of the more delicate aromas, but stabilizes it by inactivating enzymes and bacteria, and adds slightly sulfury and green-leaf notes (dimethyl sulfide, hexanal). High-temperature pasteurization or brief cooking—heating milk above 170ºF/76ºC—generates traces of many flavorful substances, including those characteristic of vanilla, almonds, and cultured butter, as well as eggy hydrogen sulfide. Prolonged boiling encourages browning or Maillard reactions between lactose and milk proteins, and generates molecules that combine to give the flavor of butterscotch.

The Development of Off-Flavors The flavor of good fresh milk can deteriorate in several different ways. Simple contact with oxygen or exposure to strong light will cause the oxidation of phospholipids in the globule membrane and a chain of reactions that slowly generate stale cardboard, metallic, fishy, paint-like aromas. If milk is kept long enough to sour, it also typically develops fruity, vinegary, malty, and more unpleasant notes.

Exposure to sunlight or fluorescent lights also generates a distinctive cabbage-like, burnt odor, which appears to result from a reaction between the vitamin riboflavin and the sulfur-containing amino acid methionine. Clear glass and plastic containers and supermarket lighting cause this problem; opaque cartons prevent it.

UNFERMENTED DAIRY PRODUCTS

Fresh milk, cream, and butter may not be as prominent in European and American cooking as they once were, but they are still essential ingredients. Milk has bubbled up to new prominence atop the coffee craze of the 1980s and '90s.

Milks

Milk has become the most standardized of our basic foods. Once upon a time, people lucky enough to live near a farm could taste the pasture and the seasons in milk fresh from the cow. City life, mass production, and stricter notions of hygiene have now put that experience out of reach. Today nearly all of our milk comes from cows of one breed, the black-and-white Holstein, kept in sheds and fed year-round on a uniform diet. Large dairies pool the milk of hundreds, even thousands of cows, then pasteurize it to eliminate microbes and homogenize it to prevent the fat from separating. The result is processed milk of no particular animal or farm or season, and therefore of no particular character. Some small dairies persist in milking other breeds, allowing their herds out to pasture, pasteurizing mildly, and not homogenizing. Their milk can have a more distinctive flavor, a rare reminder of what milk used to taste like.

Raw Milk Careful milking of healthy cows yields sound raw milk, which has its own fresh taste and physical behavior. But if it's contaminated by a diseased cow or careless handling—the udder hangs right next to the tail—this nutritious fluid soon teems with potentially dangerous microbes. The importance of strict hygiene in the dairy has been understood at least since the Middle Ages, but life far from the farms made contamination and even adulteration all too common in cities of the 18th and 19th centuries, where many children were killed by tuberculosis, brucellosis, and simple food poisoning contracted from tainted milk. In the 1820s, long before anyone knew about microbes, some books on domestic economy advocated boiling all milk before use. Early in the 20th century, national and local governments began to regulate the dairy industry and require that it heat milk to kill disease microbes.

Today very few U.S. dairies sell raw milk. They must be certified by the state and inspected frequently, and the milk carries a warning label. Raw milk is also rare in Europe.

Pasteurization and UHT Treatments In the 1860s, the French chemist Louis Pasteur studied the spoilage of wine and beer and developed a moderate heat treatment that preserved them while minimizing changes in their flavor. It took several decades for pasteurization to catch on in the dairy. Nowadays, in industrial-scale production, it's a practical necessity. Collecting and pooling milk from many different farms increases the risk that a given batch will be contaminated; and the plumbing and machinery required for the various stages of processing afford many more opportunities for contamination. Pasteurization extends the shelf life of milk by killing pathogenic and spoilage microbes and by inactivating milk enzymes, especially the fat splitters, whose slow but steady activity can make it unpalatable. Pasteurized milk stored below 40ºF/5ºC should remain drinkable for 10 to 18 days.

There are three basic methods for pasteurizing milk. The simplest is *batch* pasteurization, in which a fixed volume of milk, perhaps a few hundred gallons, is slowly agitated in a heated vat at a minimum of 145ºF/62ºC for 30 to 35 minutes. Industrial-scale operations use the *high-temperature, short-time* (HTST) method, in which milk is pumped continuously through a heat exchanger and held at a minimum of 162ºF/72ºC for 15 seconds. The batch process has a relatively mild effect on flavor, while the HTST method is hot enough to denature around 10% of the whey proteins and generate the strongly aromatic gas hydrogen sulfide (p. 87). Though this "cooked" flavor was considered a defect in the early days, U.S. consumers have come to expect it, and dairies now often intensify it by pasteurizing at well above the minimum temperature; 171ºF/77ºC is commonly used.

The third method of pasteurizing milk is the *ultra-high temperature* (UHT) method, which involves heating milk at 265–300ºF/

130–150ºC either instantaneously or for 1 to 3 seconds, and produces milk that, if packaged under strictly sterile conditions, can be stored for months without refrigeration. The longer UHT treatment imparts a cooked flavor and slightly brown color to milk; cream contains less lactose and protein, so its color and flavor are less affected.

Sterilized milk has been heated at 230–250ºF/110–121ºC for 8 to 30 minutes; it is even darker and stronger in flavor, and keeps indefinitely at room temperature.

Homogenization Left to itself, fresh whole milk naturally separates into two phases: fat globules clump together and rise to form the cream layer, leaving a fat-depleted phase below (p. 18). The treatment called *homogenization* was developed in France around 1900 to prevent creaming and keep the milk fat evenly—homogeneously—dispersed. It involves pumping hot milk at high pressure through very small nozzles, where the turbulence tears the fat globules apart into smaller ones; their average diameter falls from 4 micrometers to about 1. The sudden increase in globule numbers causes a proportional increase in their surface area, which the original globule membranes are insufficient to cover. The naked fat surface attracts casein particles, which stick and create an artificial coat (nearly a third of the milk's casein ends up on the globules). The casein particles both weigh the fat globules down and interfere with their usual clumping: and so the fat remains evenly dispersed in the milk. Milk is always pasteurized just before or simultaneously with homogenization to prevent its enzymes from attacking the momentarily unprotected fat globules and producing rancid flavors.

Homogenization affects milk's flavor and appearance. Though it makes milk taste blander—probably because flavor molecules get stuck to the new fat-globule surfaces—it also makes it more resistant to developing most off-flavors. Homogenized milk feels creamier in the mouth thanks to its increased population (around sixty-fold) of fat globules, and it's whiter, because the carotenoid pigments in the fat are scattered into smaller and more numerous particles.

Nutritional Alteration; Low-Fat Milks One nutritional alteration of milk is as old as dairying itself: skimming off the cream layer substantially reduces the fat content of the remaining milk. Today, low-fat milks are made more efficiently by centrifuging off some of the globules before homogenization. Whole milk is about 3.5% fat, low-fat milks usually 2% or 1%, and skim milks can range between 0.1 and 0.5%.

More recent is the practice of supplementing milk with various substances. Nearly all milks are fortified with the fat-soluble vitamins A and D. Low-fat milks have a thin body and appearance and are usually filled out with dried milk proteins, which can lend them a slightly stale flavor.

Powdered Milk in 13th-Century Asia

[The Tartar armies] make provisions also of milk, thickened or dried to the state of a hard paste, which they prepare in the following manner. They boil the milk, and skimming off the rich or creamy part as it rises to the top, put it into a separate vessel as butter; for so long as that remains in the milk, it will not become hard. The milk is then exposed to the sun until it dries. [When it is to be used] some is put into a bottle with as much water as is thought necessary. By their motion in riding, the contents are violently shaken, and a thin porridge is produced, upon which they make their dinner.

—Marco Polo, *Travels*

"Acidophilus" milk contains *Lactobacillus acidophilus,* a bacterium that metabolizes lactose to lactic acid and that can take up residence in the intestine (p. 47). More helpful to milk lovers who can't digest lactose is milk treated with the purified digestive enzyme lactase, which breaks lactose down into simple, absorbable sugars.

Storage Milk is a highly perishable food. Even Grade A pasteurized milk contains millions of bacteria in every glassful, and will spoil quickly unless refrigerated. Freezing is a bad idea because it disrupts milk fat globules and protein particles, which clump and separate when thawed.

Concentrated Milks A number of cultures have traditionally cooked milk down for long keeping and ease of transport. According to business legend, the American Gail Borden reinvented evaporated milk around 1853 after a rough transatlantic crossing that sickened the ship's cows. Borden added large amounts of sugar to keep his concentrated milk from spoiling. The idea of sterilizing unsweetened milk in the can came in 1884 from John Meyenberg, whose Swiss company merged with Nestlé around the turn of the century. Dried milk didn't appear until around the turn of the 20th century. Today, concentrated milk products are valued because they keep for months and supply milk's characteristic contribution to the texture and flavor of baked goods and confectionery, but without milk's water.

Condensed or *evaporated milk* is made by heating raw milk under reduced pressure (a partial vacuum), so that it boils between 110 and 140ºF/43–60ºC, until it has lost about half its water. The resulting creamy, mild-flavored liquid is homogenized, then canned and sterilized. The cooking and concentration of lactose and protein cause some browning, and this gives evaporated milk its characteristic tan color and note of caramel. Browning continues slowly during storage, and in old cans can produce a dark, acidic, tired-tasting fluid.

For *sweetened condensed milk,* the milk is first concentrated by evaporation, and then table sugar is added to give a total sugar concentration of about 55%. Microbes can't grow at this osmotic pressure, so sterilization is unnecessary. The high concentration of sugars causes the milk's lactose to crystallize, and this is controlled by seeding the milk with preformed lactose crystals to keep the crystals small and inconspicuous on the tongue (large, sandy lactose crystals are sometimes encountered as a quality defect). Sweetened condensed milk has a milder, less "cooked" flavor than evaporated milk, a lighter color, and the consistency of a thick syrup.

Powdered or *dry milk* is the result of

The Composition of Concentrated Milks

The figures are the percentages of each milk's weight accounted for by its major components.

Kind of Milk	Protein	Fat	Sugar	Minerals	Water
Evaporated milk	7	8	10	1.4	73
Evaporated skim milk	8	0.3	11	1.5	79
Sweetened condensed milk	8	9	55	2	27
Dry milk, full fat	26	27	38	6	2.5
Dry milk, nonfat	36	1	52	8	3
Fresh milk	3.4	3.7	4.8	1	87

taking evaporation to the extreme. Milk is pasteurized at a high temperature; then about 90% of its water is removed by vacuum evaporation, and the remaining 10% in a spray drier (the concentrated milk is misted into a chamber of hot air, where the milk droplets quickly dry into tiny particles of milk solids). Some milk is also freeze-dried. With most of its water removed, powdered milk is safe from microbial attack. Most powdered milk is made from low-fat milk because milk fat quickly goes rancid when exposed to concentrated milk salts and atmospheric oxygen, and because it tends to coat the particles of protein and makes subsequent remixing with water difficult. Powdered milk will keep for several months in dry, cool conditions.

Cooking with Milk Much of the milk that we use in the kitchen disappears into a mixture—a batter or dough, a custard mix or a pudding—whose behavior is largely determined by the other ingredients. The milk serves primarily as a source of moisture, but also contributes flavor, body, sugar that encourages browning, and salts that encourage protein coagulation.

When milk itself is a prominent ingredient—in cream soups, sauces, and scalloped potatoes, or added to hot chocolate, coffee, and tea—it most often calls attention to itself when its proteins coagulate. The skin that forms on the surface of scalded milk, soups, and sauces is a complex of casein, calcium, whey proteins, and trapped fat globules, and results from evaporation of water at the surface and the progressive concentration of proteins there. Skin formation can be minimized by covering the pan or whipping up some foam, both of which minimize evaporation. Meanwhile, at the bottom of the pan, the high, dehydrating temperature transmitted from the burner causes a similar concentration of proteins, which stick to the metal and eventually scorch. Wetting the pan with water before adding milk will reduce protein adhesion to the metal; a heavy, evenly conducting pan and a moderate flame help minimize scorching, and a double boiler will prevent it (though it's more trouble).

Between the pan bottom and the surface, particles of other ingredients can cause curdling by providing surfaces to which the milk proteins can stick and clump together. And acid in the juices of all fruits and vegetables and in coffee, and astringent tannins in potatoes, coffee, and tea, make milk proteins especially sensitive to coagulation and curdling. Because bacteria slowly sour milk, old milk may be acidic enough to curdle instantly when added to hot coffee or tea. The best insurance against curdling is fresh milk and careful control of the burner.

Cooking Sweetened Condensed Milk Because it contains concentrated protein

Intentionally Curdled Milk

For most cooks most of the time, curdled milk betokens crisis: the dish has lost its smoothness. But there are plenty of dishes in which the cook intentionally causes the milk proteins to clot precisely for the textural interest this creates. The English *syllabub* was sometimes made by squirting warm milk directly from the udder into acidic wine or juice; and in the 17th century, the French writer Pierre de Lune described a reduced milk "marbled" by the addition of currant juice. More contemporary examples include roast pork braised in milk, which reduces to moist brown nuggets; the Kashmiri practice of cooking milk down to resemble browned ground meat; and eastern European summertime cold milk soups like the Polish *chlodnik*, thickened by the addition of "sour salt," or citric acid.

and sugar, sweetened condensed milk will "caramelize" (actually, undergo the Maillard browning reaction, p. 778) at temperatures as low as the boiling point of water. This has made cans of sweetened condensed milk a favorite shortcut to a creamy caramel sauce: many people simply put the can in a pot of boiling water or a warm oven and let it brown inside. While this does work, it is potentially dangerous, since any trapped air will expand on heating and may cause the can to burst open. It's safer to empty the can into an open utensil and then heat it on the stovetop, in the oven, or in the microwave.

Milk Foams A foam is a portion of liquid filled with air bubbles, a moist, light mass that holds its shape. A meringue is a foam of egg whites, and whipped cream is a foam of cream. Milk foams are more fragile than egg foams and whipped cream, and are generally made immediately before serving, usually as a topping for coffee drinks. They prevent a skin from forming on the drink, and keep it hot by insulating it and preventing evaporative cooling.

Milk owes its foaming power to its proteins, which collect in a thin layer around the pockets of air, isolate them, and prevent the water's strong cohesive forces from popping the bubbles. Egg foams are also stabilized by proteins (p. 101), while the foam formed by whipping cream is stabilized by fat (below, p. 31). Milk foams are more fragile and short-lived than egg foams because milk's proteins are sparse—just 3% of the milk's weight, where egg white is 10% protein—and two-thirds of the milk proteins are resistant to being unfolded and coagulated into a solid network, while most of the egg proteins readily do so. However, heat around 160ºF/70ºC does unfold the whey proteins (barely 1% of milk's weight). And if they unfold at the air-water boundary of a bubble wall, then the force imbalance does cause the proteins to bond to each other and briefly stabilize the foam.

Milks and Their Foams Some milks are better suited to foaming than others. Because the whey proteins are the critical stabilizers, milks that are fortified with added protein—usually reduced-fat and skim milks—are most easily foamed. Full-fat foams, on the other hand, are fuller in texture and flavor. Milk should always be as fresh as possible, since milk that has begun to sour can curdle when heated.

India's Galaxy of Cooked Milks

For sheer inventiveness with milk itself as the primary ingredient, no country on earth can match India. Its dozens of variations on the theme of cooked-down milk, many of them dating back a thousand years, stem from a simple fact of life in that warm country: the simplest way to keep milk from souring is to boil it repeatedly. Eventually it cooks down to a brown, solid paste with about 10% moisture, 25% lactose, 20% protein and 20% butterfat. Even without added sugar, *khoa* is almost a candy, so it makes sense that over time, it and the intermediate concentrations that precede it became the basis for the most widely made Indian milk sweets. Doughnut-like fried *gulabjamun* and fudge-like *burfi* are rich in lactose, calcium, and protein: a glass of milk distilled into a morsel.

A second, separate constellation of Indian milk sweets is based on concentrating the milk solids by curdling them with heat and either lime juice or sour whey. The drained curds form a soft, moist mass known as *chhanna,* which then becomes the base for a broad range of sweets, notably porous, springy cakes soaked in sweetened milk or syrup (*rasmalai, rasagollah*).

Espresso Steamers: Simultaneous Bubbles and Heat Milk foams are usually made with the help of the steam nozzle on an espresso coffee machine. Steaming milk accomplishes two essential things simultaneously: it introduces bubbles into the milk, and it heats the bubbles enough to unfold and coagulate the whey proteins into a stabilizing web. Steam itself does not make bubbles: it is water vapor, and simply condenses into the colder water of the milk. Steam makes bubbles by splashing milk and air together, and it does this most efficiently when the nozzle is just below the milk surface.

One factor that makes steaming tricky is that very hot milk doesn't hold its foam well. A foam collapses when gravity pulls the liquid out of the bubble walls, and the hotter the liquid, the faster it drains. So you have to use a large enough volume of cold milk—at least ⅔ cup/150 ml—to make sure that the milk doesn't heat up too fast and become too runny before the foam forms.

Cream

Cream is a special portion of milk that is greatly enriched with fat. This enrichment occurs naturally thanks to the force of gravity, which exerts more of a pull on the milk's water than on the less dense fat globules. Leave a container of milk fresh from the udder to stand undisturbed, and the globules slowly rise through the water and crowd together at the top. The concentrated cream layer can then be skimmed off from the fat-depleted "skim" milk below. Milk with 3.5% fat will naturally yield cream that is about 20%.

We value cream above all for its feel. *Creaminess* is a remarkable consistency, perfectly balanced between solidity and fluidity, between persistence and evanescence. It's substantial, yet smooth and seamless. It lingers in the mouth, yet offers no resistance to teeth or tongue, nor becomes merely greasy. This luxurious sensation results from the crowding of the fat glob-

Keys to Foaming Milk

To get a good volume of milk foam from the steam attachment on an espresso machine:

- Use fresh milk right out of the refrigerator, or even chilled for a few minutes in the freezer.
- Start with at least ⅔ cup/150 ml of milk in a container that will hold at least double the initial volume.
- Keep the nozzle at or just under the milk surface so that it froths continuously with a moderate flow of steam.

To foam a small volume of milk without steam, separate the foaming and heating steps:

- Pour cold, fresh milk into a jar, tighten the lid, and shake it vigorously for 20 seconds or until the contents have doubled in volume. (Or froth in a plunger-style coffee maker, whose fine screen produces an especially thick, creamy foam.)
- Then stabilize the foam: remove the lid, place the jar in the microwave, and heat on high for about 30 seconds, or until the foam rises to the top of the jar.

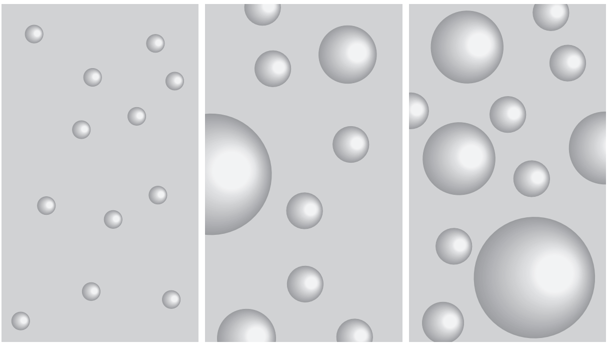
ules, which are far too small for our senses to distinguish, into a small volume of water, whose free movement is thus impeded and slowed.

In addition to its appealing texture, cream has distinctive "fatty" aroma notes from molecules also found in coconut and peach (lactones). And it offers the virtue of being a robust, forgiving ingredient. Milk contains roughly equal weights of protein and fat, while in cream fat outweighs protein by at least 10 to 1. Thanks to this dilution of the protein, cream is less likely to curdle. And thanks to its concentration of fat globules, it can be inflated into whipped cream: a far more substantial and stable foam than milk alone can make.

Though it has certainly been appreciated since the beginning of dairying, cream spoils faster than the butter that could be made from it, and so it played a minor role in all but farmhouse kitchens until fairly recently. By the 17th century, French and English cooks were frothing cream into imitation snow; the English exploited its layering nature to pile cream skins in the form of a cabbage, and used long, gentle heating to produce solid, nutty "clouted" cream. Cream's heyday arrived in the 18th century, when it went into cakes, puddings, and such savory dishes as fricassees, stews, and boiled vegetables, and became popular in frozen form as ice cream. The popularity of cream declined in the 20th century with the nutritional condemnation of saturated fats, so much so that in many parts of the United States it's only available in the long-keeping ultrapasteurized form.

Making Cream The natural separation of cream from milk by means of gravity takes 12 to 24 hours, and was superseded late in the 19th century by the merry-go-round forces of the French centrifugal separator. Once separated, the cream is pasteurized. In the United States, the minimum temperatures for pasteurizing cream are higher than the milk minimum (for 20% fat or less, 30 minutes at 155ºF/68ºC; otherwise at 165ºF/74ºC). "Ultrapasteurized" cream is heated for 2 seconds at 280ºF/140ºC (like UHT-treated milk, p. 22; however the cream is not packaged under strictly sterile conditions, and so is kept refrigerated). Under refrigeration, ordinary pasteurized cream keeps for about 15 days before bacterial activity turns it bitter and rancid; ultrapasteurized cream, which has a stronger cooked flavor, keeps for several weeks. Normally cream is not homogenized because this makes it harder to whip, but long-keeping ultrapasteurized cream and relatively thin half-and-half are usually homogenized to prevent continuing slow separation in the carton.

The Importance of Fat Content Cream is manufactured with a number of different fat levels and consistencies, each for particular purposes. Light creams are poured into coffee or onto fruit; heavy creams are whipped or used to thicken sauces; clotted



Fat globules in milk and cream. Left to right: *Fat globules in homogenized milk (3.5% fat), and in unhomogenized light cream (20% fat), and in heavy cream (40% fat). The more numerous fat globules in cream interfere with the flow of the surrounding fluid and give cream its full-bodied consistency.*

or "plastic" creams are spread onto breads, pastries, or fruit. The proportion of fat determines both a cream's consistency and its versatility. Heavy cream can be diluted with milk to approximate light cream, or whipped to make a spreadable semisolid. Light cream and half-and-half contain insufficient numbers of fat globules to stabilize a whipped foam (p. 32), or to resist curdling in a sauce. Whipping cream, at between 30 and 40% fat, is the most versatile formulation.

Stability in Cooking How does a high fat content permit the cook to boil a mixture of heavy cream and salty or acidic ingredients without curdling it, as when dissolving pan solids or thickening a sauce? The key seems to be the ability of the fat globule's surface membrane to latch onto a certain amount of the major milk protein, casein, when milk is heated. If the fat globules account for 25% or more of the cream's weight, then there's a sufficient area of globule surface to take most of the casein out of circulation, and no casein curds can form. At lower fat levels, there's both a smaller globule surface area *and* a greater proportion of the casein-carrying water phase. Now the globule surfaces can only

Kinds of Cream

U.S. Term	European Term	Fat Content, %	Use
Half-and-half		12 (10.5–18)	Coffee, pouring
	*Crème légère**	12–30	Coffee, pouring, enriching sauces, soups, etc., whipping
	Single cream	18+	Coffee, pouring
Light cream		20 (18–30)	Coffee, pouring (seldom available)
	Coffee cream	25	Coffee, pouring
Light whipping cream		30–36	Pouring, enriching, whipping
	Crème fraîche† (*fleurette* or *épaisse*)*	30–40	Pouring, enriching, whipping (if rich, spreading)
Whipping cream		35+	Pouring, enriching, whipping
Heavy whipping cream		38 (36+)	Pouring, enriching, whipping
	Double cream	48+	Spreading
	Clotted cream	55+	Spreading
Plastic cream		65–85	Spreading

**légère*: "light"; *fleurette*: "liquid"; *épaisse*: "thick" due to bacterial culture

†*fraîche*: "fresh, cool, new." In France, *crème fraîche* may be either "sweet" or cultured with lactic acid bacteria; in the United States, the term always means cultured, tart, thick cream. See p. 49.

absorb a small fraction of the casein, and the rest bonds together and coagulates when heated. (This is why acid-curdled mascarpone cheese can be made from light cream, but not from heavy cream.)

Problems with Cream: Separation A common problem with unhomogenized cream is that it continues to separate in the carton: the fat globules slowly rise and concentrate further into a semisolid layer at the top. At refrigerator temperatures, the fat inside the globules forms solid crystals whose edges break through the protective globule membrane, and these slightly protruding fat crystals get stuck to each other and form microscopic butter grains.

Clotted Creams These days cooks generally consider the separation and solidification of cream a nuisance. In the past, and in present-day England and the Middle East, congealed cream has been and is appreciated for its own sake. The cooks of 17th-century England would patiently lift the skins from shallow dishes of cream and arrange them in wrinkled mounds to imitate the appearance of a cabbage. Cabbage cream is now a mere curiosity. But the 16th-century English invention called *clotted* cream (and its Turkish and Afghan relatives *kaymak* and *qymaq*) remain vital traditions.

Old-fashioned clotted cream is made by heating cream just short of the boil in shallow pans for several hours, then letting it cool and stand for a day or so, and removing the thick solid layer. Heat accelerates the rise of the fat globules, evaporates some of the water, melts some of the aggregated globules into pockets of butterfat, and creates a cooked flavor. The result is a mix of thick, granular, fatty areas and thin, creamy ones, with a rich, nutty flavor and a straw-colored surface. Clotted cream is around 60% fat, and is spread onto scones and biscuits and eaten with fruit.

Whipped Cream The miraculous thing about whipped cream is that simple physical agitation can transform a luscious but

Food Words: *Cream, Crème, Panna*

The English name for the fat-rich portion of milk, like the French word from which it derives, has associations that are startling but appropriate to its status as a textural ideal.

Before the Norman Conquest, and to this day in some northern dialects, the English word for cream was *ream,* a simple offshoot of the Indo-European root that also gave the modern German *Rahm.* But the French connection introduced a remarkable hybrid term. In 6th-century Gaul, fatty milk was called *crama,* from the Latin *cremor lactis,* or "heat-thickened substance of milk." Then in the next few centuries it somehow became crossed with a religious term: *chreme,* or "consecrated oil," which stems from the Greek word *chriein,* "to anoint," that gave us *Christ,* "the anointed one." So in France *crama* became *crème,* and in England *ream* gave way to *cream.*

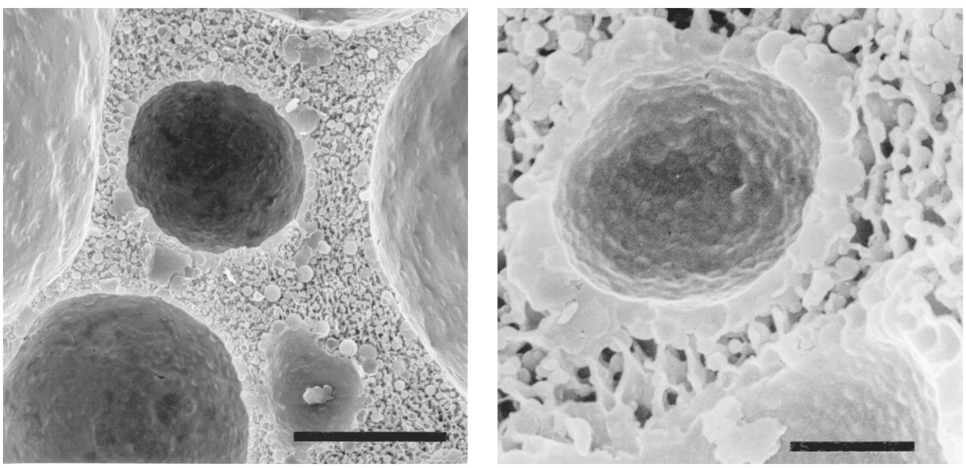
Why this confusion of ancient ritual with rich food? Linguistic accident or error, perhaps. On the other hand, anointing oil and butterfat *are* essentially the same substance, so perhaps it was inspiration. In the monastic or farm kitchens of Normandy, the addition of cream to other foods may have been considered not just an enrichment, but a kind of blessing.

The Italian word for cream, *panna,* has been traced back to the Latin *pannus,* or "cloth." This is apparently a homely allusion to the thin covering that cream provides for the milk surface.

unmanageable liquid into an equally luscious but shapeable "solid." Like foamed milk, whipped cream is an intimate intermingling of liquid and air, with the air divided into tiny bubbles and the cream spread out and immobilized in the microscopically thin bubble walls. Common as it is today, this luxurious, velvety foam was very laborious to make until 1900. Before then, cooks whipped naturally separated cream for an hour or more, periodically skimming off the foam and setting it aside to drain. The key to a stable foam of the whole mass of cream is enough fat globules to hold all the fluid and air together, and naturally separated cream seldom reaches that fat concentration, which is about 30%. It took the invention of the centrifugal separator to produce easily whipped cream.

How Fat Stabilizes Foamed Cream Unlike the protein foams of egg white, egg yolk, and milk, the cream foam is stabilized by fat. Initially, the whisk introduces short-lived air bubbles into the cream. After the first half-minute or so, the bubble walls begin to be stabilized by the *de*stabilization of the fat globules. As the globules are knocked all around and into each other by the whipping, parts of their protective membranes are stripped away by the shearing action of the whisk, and by the force imbalance in the air bubble walls. The patches of naked fat, which by their nature avoid contact with water, settle in one of two regions in the cream: either facing the air pocket in the bubble walls, or stuck to a patch of naked fat on another globule. The fat globules thus form walls around the air bubbles, and connections between neighboring walls: and so a continuous network develops. This network of solid fat spheres not only holds the air bubbles in place, but also prevents the intervening pockets of fluid from moving very far. And so the foam as a whole takes on a definite, persistent structure.

If the beating continues past the point at which a fat network has just barely formed, the gathering of the fat globules continues also, but this process now *de*stabilizes the foam. The fine globule clusters coalesce with each other into ever coarser masses of butterfat, and the pockets of air and fluid that they hold in place coarsen as well. The foam loses volume and weeps, and the vel-



Whipped cream as seen through the scanning electron microscope. Left: *A view showing the large cavity-like air bubbles and smaller spherical fat globules (the black bar represents 0.03 mm).* Right: *Close-up of an air bubble, showing the layer of partly coalesced fat that has stabilized the bubble (the bar represents 0.005 mm).*

vety texture of the perfectly whipped cream becomes granular. The butter grains in overwhipped cream leave a greasy residue in the mouth.

The Importance of Cold Because even mild warmth softens the butterfat skeleton of a cream foam, and liquid fat will collapse the air bubbles, it's essential to keep cream cold while it's whipped. It should start out at the low end of 40–50ºF/5–10ºC, and bowl and beaters should be chilled as well, since both air and beating will quickly warm everything. Ideally, the cream is "aged" in the refrigerator for 12 hours or more before whipping. Prolonged chilling causes some of the butterfat to form crystalline needles that hasten the membrane stripping and immobilize the small portion of fat that's liquid even in cold cream. Cream that has been left at room temperature and chilled just before use leaks bubble-deflating liquid fat from the beginning of whipping, never rises very high, and more easily becomes granular and watery.

How Different Creams Behave When Whipped Cream for whipping must be sufficiently rich in fat to form a continuous skeleton of globules. The minimum fat concentration is 30%, the equivalent of "single" or "light whipping" cream. "Heavy" cream, at 38 to 40% fat, will whip faster than light cream, and forms a stiffer, denser, less voluminous foam. It also leaks less fluid, and so is valued for use in pastries and baked goods, and for piping into decorative shapes. For other purposes, heavy cream is usually diluted with a quarter of its volume of milk to make 30% cream and a lighter, softer foam.

The fat globules in homogenized cream are smaller and more thickly covered with milk proteins. Homogenized cream therefore forms a finer-textured foam, and takes at least twice as long to whip (it's also harder to overwhip to the granular stage). The cook can cut the whipping time of any cream by slightly acidifying it (1 teaspoon/5 ml lemon juice per cup/250 ml), which makes the proteins in its globule membranes easier to strip away.

Methods: Hand, Machine, Pressurized Gas Cream can be foamed by several different methods. Whisking by hand takes more time and physical exertion than an electric beater, but incorporates more air and produces a greater volume. The lightest, fluffiest whipped cream is produced with the help of pressurized gas, usually nitrous oxide (N_2O). The most familiar

Early Whipped Cream

My Lord of S. Alban's Cresme Fouettee

Put as much as you please to make, of sweet thick cream into a dish, and whip it with a bundle of white hard rushes, (of such as they make whisks to brush cloaks) tied together, till it come to be very thick, and near a buttery substance. If you whip it too long, it will become butter. About a good hour will serve in winter. In summer it will require an hour and a half. Do not put in the dish you will serve it up in, till it be almost time to set it upon the table. Then strew some powdered fine sugar into the bottom of the dish it is to go in, and with a broad spatule lay your cream upon it: when half is laid in, strew some more fine sugar upon it, and then lay in the rest of the cream (leaving behind some whey that will be in the bottom) and strew some more sugar upon that.

—Sir Kenelm Digby, *The Closet Opened,* 1669 gas-powered device is the aerosol can, which contains a pressurized mixture of ultrapasteurized cream and dissolved gas. When the nozzle is opened and the mixture released, the gas expands instantly and explodes the cream into a very light froth. There is also a device that aerates ordinary fresh cream with a replaceable canister of nitrous oxide, which is released in the nozzle and causes great turbulence as it mixes with the cream.

Butter and Margarine

These days, if a cook actually manages to *make* butter in the kitchen, it's most likely a disaster: a cream dish has been mishandled and the fat separates from the other ingredients. That's a shame: all cooks should relax now and then and intentionally overwhip some cream! The coming of butter is an everyday miracle, an occasion for delighted wonder at what the Irish poet Seamus Heaney called "coagulated sunlight" "heaped up like gilded gravel in the bowl." Milkfat is indeed a portion of the sun's energy, captured by the grasses of the field and repackaged by the cow in scattered, microscopic globules. Churning milk or cream damages the globules and frees their fat to stick together in ever larger masses, which we eventually sieve into the golden hoard that imparts a warm, sweet richness to many foods.

Ancient, Once Unfashionable All it takes to separate the fat from milk is 30 seconds of sloshing, so butter was no doubt discovered in the earliest days of dairying. It has long been important from Scandinavia to India, where nearly half of all milk production goes to making butter for both cooking and ceremonial purposes. Its heyday came much later in northern Europe, where throughout the Middle Ages it was eaten mainly by peasants. Butter slowly infiltrated noble kitchens as the only animal fat allowed by Rome on days of abstention from meat. In the early 16th century it was also permitted during Lent, and the rising middle classes adopted the rustic coupling of bread and butter. Soon the English were notorious for serving meats and vegetables swimming in melted butter, and cooks throughout Europe exploited butter in a host of fine foods, from sauces to pastries.

Normandy and Brittany in northwest France, Holland, and Ireland became especially renowned for the quality of their butter. Most of it was made on small farms using cream that was pooled from several milkings, and was therefore a day or two old and somewhat soured by lactic acid bacteria. Continental Europe still prefers the flavor of this lightly fermented "cultured" butter to the "sweet cream" butter made common in the 19th century by the use of ice, the development of refrigeration, and the mechanical cream separator.

Around 1870, a shortage of butter in France led to the invention of an imitation, *margarine,* which could be made from a variety of cheap animal fats and vegetable oils. More margarine than butter is now consumed in the United States and parts of Europe.

Making Butter Butter making is in essence a simple but laborious operation: you agitate a container of cream until the fat globules are damaged and their fat leaks out and comes together into masses large enough to gather.

Preparing the Cream For butter making, cream is concentrated to 36–44% fat. The cream is then pasteurized, in the United States usually at 185ºF/85ºC, a high temperature that develops a distinct cooked, custardy aroma. After cooling, the cream for cultured butter may be inoculated with lactic acid bacteria (see p. 35). The sweet or cultured cream is then cooled to about 40ºF/5ºC and "aged" at that temperature for at least eight hours so that about half of the milk fat in the globules forms solid crystals. The number and size of these crystals help determine the how quickly and completely the milk fat separates, as well as the final texture of the butter. The properly aged cream is then warmed a few degrees Fahrenheit and churned.

Churning Churning is accomplished by a variety of mechanical devices that may take 15 minutes or a few seconds to damage the fat globules and form the initial grains of butter. The fat crystals formed during aging distort and weaken the globule membranes so that they rupture easily. When damaged globules collide with each other, the liquid portion of their fat flows together to make a continuous mass, and these grow as churning continues.

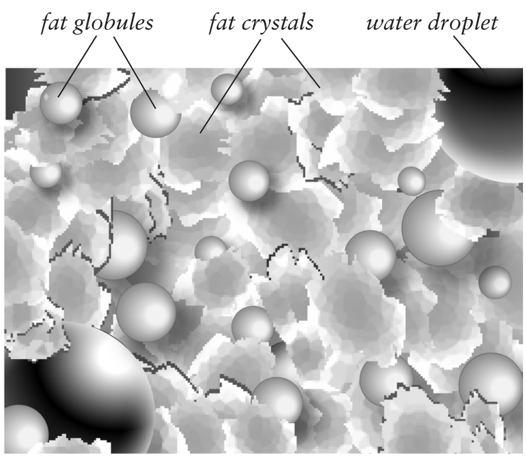
Working Once churning generates the desired size of butter grains, often the size of a wheat seed, the water phase of the cream is drained off. This is the original buttermilk, rich in free globule membrane material and with about 0.5% fat (p. 50). The solid butter grains may be washed with cold water to remove the buttermilk on their surfaces. The grains are then "worked," or kneaded together to consolidate the semisolid fat phase and to break up the embedded pockets of buttermilk (or water) into droplets around 10 micrometers in diameter, or about the size of a large fat globule. Cows that get little fresh pasturage and its orange carotene pigments produce pale milk fat; the butter maker can compensate for this by adding a dye such as annatto (p. 423) or pure carotene during the working. If the butter is to be salted, either fine granular salt or a strong brine goes in at this stage as well. The butter is then stored, blended, or immediately shaped and packaged.

Kinds of Butter Butter is made in several distinct styles, each with its own particular qualities. It's necessary to read labels carefully to learn whether a given brand has been made with plain cream, fermented cream, or cream flavored to taste like fermented cream.

Raw cream butter, whether sweet or cultured, is now nearly extinct in the United States and a rarity even in Europe. It is prized for its pure cream flavor, without the cooked-milk note due to pasteurization. The flavor is fragile; it deteriorates after about 10 days unless the butter is frozen.

Sweet cream butter is the most basic, and the commonest in Britain and North America. It's made from pasteurized fresh cream, and in the United States must be at least 80% fat and no more than 16% water; the remaining 4% is protein, lactose, and salts contained in the buttermilk droplets.

Salted sweet cream butter contains between 1 and 2% added salt (the equivalent of 1–2 teaspoons per pound/5–10 gm



The structure of butter, which is about 80% milk fat and 15% water. The fat globules, solid crystals, and water droplets are embedded in a continuous mass of semisolid "free" fat that coats them all. A high proportion of ordered crystals imparts a stiff firmness to cold butter, while free fat lends spreadability and the tendency to leak liquid fat as it warms and softens.

per 500 gm). Originally salt was added as a preservative, and at 2%, the equivalent of about 12% in the water droplets, it still is an effective antimicrobial agent.

Cultured cream butter, the standard in Europe, is the modern, controlled version of the commonest preindustrial butter, whose raw cream had been slightly soured by the action of lactic acid bacteria while it slowly separated in the pan before churning. Cultured butter tastes different: the bacteria produce both acids and aroma compounds, so the butter is noticeably fuller in flavor. One particular aroma compound, diacetyl, greatly intensifies the basic butter flavor itself.

There are several different methods for manufacturing cultured butter or something like it. The most straightforward is to ferment pasteurized cream with cream-culture bacteria (p. 49) for 12 to 18 hours at cool room temperature before churning. In the more efficient method developed in the Netherlands in the 1970s and also used in France, sweet cream is churned into butter, and then the bacterial cultures and preformed lactic acid are added; flavor develops during cold storage. Finally, the manufacturer can simply add pure lactic acid and flavor compounds to sweet cream butter. This is an artificially flavored butter, not a cultured butter.

European-style butter, an American emulation of French butter, is a cultured butter with a fat content higher than the standard 80%. France specifies a minimum fat content of 82% for its butter, and some American producers aim for 85%. These butters contain 10–20% less water, which can be an advantage when making flaky pastries (p. 563).

Whipped butter is a modern form meant to be more spreadable. Ordinary sweet butter is softened and then injected with about a third its volume of nitrogen gas (air would encourage oxidation and rancidity). Both the physical stress and the gas pockets weaken the butter structure and make it easier to spread, though it remains brittle at refrigerator temperature.

Specialty butters are made in France for professional bakers and pastry chefs. *Beurre cuisinier, beurre pâtissier,* and *beurre concentré* are almost pure butterfat, and are made from ordinary butter by gently melting it and centrifuging the fat off of the water and milk solids. It can then be recooled as is, or slowly crystallized and separated into fractions that melt at temperatures from 80ºF/27ºC to 104ºF/40ºC, depending on the chef's needs.

Butter Consistency and Structure Well made butters can have noticeably different consistencies. In France, for example, butter from Normandy is relatively soft and favored for spreading and making sauces—Elizabeth David said, "When you get melted butter with a trout in Normandy it is difficult to believe that it is not cream"—while butter from the Charentes is firmer, and preferred for making pastries. Many dairies will often produce softer butter in the summer than they do in the winter. The consistency of butter reflects its microscopic structure, and this is strongly influenced by two factors: what the cows eat, and how the butter maker handles their milk. Feeds rich in polyunsaturated fats, especially fresh pasturage, produce softer butters; hay and grain harder ones. The butter maker also influences consistency by the rate and degree of cooling to which he subjects the cream during the aging period, and by how extensively he works the new butter. These conditions control the relative proportions of firming crystalline fat and softening globular and free fat.

Keeping Butter Because its scant water is dispersed in tiny droplets, properly made butter resists gross contamination by microbes, and keeps well for some days at room temperature. However, its delicate flavor is easily coarsened by simple exposure to the air and to bright light, which break fat molecules into smaller fragments that smell stale and rancid. Butter also readily absorbs strong odors from its surroundings. Keep reserves in the freezer, and daily butter in the cold and dark as much as possible. Rewrap remainders airtight, preferably with the original foiled paper and not with aluminum foil; direct contact with metal can hasten fat oxidation, particularly in salted butter. Translucent, dark yellow patches on the surface of a butter stick are areas where the butter has been exposed to the air and dried out; they taste rancid and should be scraped off.

Cooking with Butter Cooks use butter for many different purposes, from greasing cake pans and soufflé molds to flavoring butterscotch candies. Here are notes on some of its more prominent roles. The important role of butter in baking is covered in chapter 10.

Butter as Garnish: Spreads, Whipped Butters Good plain bread spread with good plain butter is one of the simplest pleasures. We owe butter's buttery consistency to the peculiar melting behavior of milk fat, which softens and becomes spreadable around 60ºF/15ºC, but doesn't begin to melt until 85ºF/30ºC.

This workable consistency also means that it's easy to incorporate other ingredients into the butter, which then carries their flavor and color and helps apply them evenly to other foods. Composed butters are masses of room-temperature butter into which some flavoring and/or coloring has been kneaded; these can include herbs, spices, stock, a wine reduction, cheese, and pounded seafood. The mixture can then be spread on another food, or refrigerated, sliced, and melted into a butter sauce when put onto a hot meat or vegetable. And whipped butter prepared by the cook is butter lightened by the incorporation of some air, and flavored with about half its volume of stock, a puree, or some other liquid, which becomes dispersed into the butter fat in small droplets.

***Butter as Sauce: Melted Butter,* Beurre Noisette, *and* Beurre Noir** Perhaps the simplest of sauces is the pat of butter dropped on a heap of hot vegetables, or stirred into rice or noodles, or drawn across the surface of an omelet or steak to give a sheen. Melted butter can be enlivened with lemon juice, or "clarified" to remove the milk solids (see below). *Beurre noisette* and *beurre noir,* "hazel" and "black" butter, are melted butter sauces that the French have used since medieval times to enrich fish, brains, and vegetables. Their flavor is deepened by heating the butter to about 250ºF/120ºC until its water boils off and the molecules in the white residue, milk sugar and protein, react with each other to form brown pigments and new aromas (the browning reaction, p. 777). Hazel butter is cooked until it's golden brown, black butter until it's dark brown (truly black butter is acrid). They're often balanced with vinegar or lemon juice, which should be added only after the butter has cooled below the boiling point; otherwise the cold liquid will cause spattering and the lemon solids may brown. On their own, they lend a rich nutty flavor to baked goods.

The emulsified butter sauces—*beurre blanc,* hollandaise, and their relatives—are described in chapter 11.

Clarified Butter *Clarified* butter is butter whose water and milk solids have been removed, leaving essentially pure milk fat that looks beautifully clear when melted and that is better suited for frying (the milk solids scorch at relatively low frying temperatures). When butter is gently heated to the boiling point of water, the water bubbles to the top, where the whey proteins form a froth. Eventually all the water evaporates, the bubbling stops, and the froth dehydrates. This leaves a skin of dry whey protein on top, and dry casein particles at the bottom. Lift off the whey skin, pour the liquid fat off of the casein residue, and the purification is complete.

Frying with Butter Butter is sometimes used for frying and sautéing. It has the advantage that its largely saturated fats are resistant to being broken down by heat, and so don't become gummy the way unsaturated oils do. It has the disadvantage that its milk solids brown and then burn around 250ºF, 150º below the smoke point of many vegetable oils. Adding oil to butter does not improve its heat tolerance. Clarifying does; butter free of milk solids can be heated to 400ºF/200ºC before burning.

Margarine and Other Dairy Spreads

Margarine has been called "a creation of political intuition and scientific research." It was invented by a French chemist in 1869, three years after Napoleon III had offered funds for the development of an inexpensive food fat to supplement the inadequate butter supply for his poorly nourished but growing urban populace. Others before Hippolyte Mège-Mouriès had modified solid animal fats, but he had the novel idea of flavoring beef tallow with milk and working the mixture like butter.

Margarine caught on quickly in the major European butter producers and exporters—Holland, Denmark, and Germany—in part because they had surplus skim milk from butter making that could be used to flavor margarine. In the United States large-scale production was underway by 1880. Here, the dairy industry and its allies in government put up fierce resistance in the form of discriminatory taxes that persisted into the 1970s. Today, basic margarine remains cheap compared to butter, and Americans consume more than twice as much margarine as butter. Scandinavia and northern Europe also favor margarine, while France and Britain still give a substantial edge to butter.

The Rise of Vegetable Margarine Modern margarine is now made not from solid animal fats, but from normally liquid vegetable oils. This shift was made possible around 1900 by German and French chemists who developed the process of *hydrogenation,* which hardens liquid oils by altering the structures of their fatty acids (p. 801). Hydrogenation allowed manufacturers to make a butter substitute that spreads easily even at refrigerator temperature, where butter is unusably hard. An unanticipated bonus for the shift to vegetable oils was the medical discovery after World War II that the saturated fats typical of meats and dairy products raise blood cholesterol levels and the risk of heart disease. The ratio of saturated to unsaturated fat in hard stick margarine is only 1 to 3, where in butter it is 2 to 1. Recently, however, scientists have found

Indian Clarified Butter: *Ghee*

In India, clarified butter is the most eminent of all foods. In addition to being used as an ingredient and frying oil, it is an emblem of purity, an ancient offering to the gods, the fuel of holy lamps and funeral pyres. Ghee (from the Sanskrit for "bright") was born of necessity. Ordinary butter spoils in only ten days in much of the country, while the clarified fat keeps six to eight months. Traditionally, ghee has been made from whole cow or buffalo milk that is soured by lactic acid bacteria into yogurt-like *dahi,* then churned to obtain butter. Today, industrial manufacturers usually start with cream. The preliminary souring improves both the quantity of butter obtained and its flavor; ghee made from sweet cream is said to taste flat. The butter is heated to 190ºF/90ºC to evaporate its water, then the temperature is raised to 250ºF/120ºC to brown the milk solids, which flavors the ghee and generates antioxidant compounds that delay the onset of rancidity. The brown residue is then filtered off (and mixed with sugar to make sweets), leaving the clear liquid ghee.

that *trans fatty acids* produced by hydrogenation actually raise blood cholesterol levels (see box). There are other methods for hardening vegetable oils that don't produce trans fatty acids, and manufacturers are already producing "trans free" margarines and shortenings.

Making Margarine The gross composition of margarine is the same as butter's: a minimum of 80% fat, a maximum of 16% water. The water phase is either fresh or cultured skim milk, or skim milk reconstituted from powder. Salt is added for flavor, to reduce spattering during frying, and as an antimicrobial agent. In the United States, the fat phase is blended from soybean, corn, cottonseed, sunflower, canola, and other oils. In Europe, lard and refined fish oils are also used. The emulsifier lecithin is added (0.2%) to stabilize the water droplets and reduce spattering in the frying pan; coloring agents, flavor extracts, and vitamins A and D are also incorporated. Nitrogen gas may be pumped in to make a whipped, softer spread.

Kinds of Margarine and Related Spreads *Stick* and *tub margarines* are the two most common kinds. They are formulated to approximate the spreadable consistency of butter at room temperature, and to melt in the mouth. Stick margarine is only slightly softer than butter in the refrigerator, and like butter can be creamed with sugar to make icings. Tub margarine is substantially less saturated and easily spreadable even at 40ºF/5ºC, but too soft to cream or to use in layered pastries.

Reduced-fat spreads contain less oil and more water than standard margarines, rely on carbohydrate and protein stabilizers, and aren't suited to cooking. The stabilizers can scorch in the frying pan. If used to replace butter or margarine in baking, high-moisture spreads throw liquid-solid proportions badly out of balance. Very-low-fat and no-fat spreads contain so much starch, gum, and/or protein that there's nothing there to melt when heated: they dry out and eventually burn.

Specialty margarines are generally available only to professional bakers. Like the original French oleomargarine, they some-

Hydrogenation By-Products: Trans Fatty Acids

Trans fatty acids are unsaturated fatty acids that nevertheless behave more like saturated fatty acids (p. 801). They're formed in the hydrogenation process, and are the reason that margarines can be as solid as butter and yet contain half the saturated fat; the trans unsaturated fats contribute a great deal to margarine firmness. Trans unsaturated fats are also less prone to oxidation or heat damage and make cooking oils more stable.

Trans fatty acids have come under scrutiny due to the likelihood that they may contribute to human heart disease. Research has shown that they not only raise undesirable LDL cholesterol levels in the blood as saturated fats do, they also lower desirable HDL levels. Manufacturers are now modifying their processing methods to lower trans fatty acids levels in U.S. margarines and cooking oils from the present levels, which reach 20–50% of total fatty acids in hard margarines (less in softer products).

Margarine manufacturers are not the only producers of trans fatty acids: the microbes in animal rumens are too! Thanks to their activity, the fat in milk, butter, and cheese averages 5% trans fatty acids, and the meat fat of ruminant animals—beef and lamb—ranges from 1 to 5%.

times contain beef tallow. They're formulated to have a firm but spreadable consistency over a much broader temperature range than butter (p. 562).

Ice Cream

Ice cream is a dish that manages to heighten the already remarkable qualities of cream. By freezing it, we make it possible to taste the birth of creaminess, the tantalizing transition from solidity to fluidity. But it was no simple matter to freeze cream in a way that does it justice.

The Invention and Evolution of Ice Cream Plain frozen cream is hard as a rock. Sugar makes it softer, but also lowers its freezing point (the dissolved sugar molecules get in the way as the water molecules settle into ordered crystals). So sweetened cream freezes well below the freezing point of pure water, and can't freeze in the slush that forms when a warm object is placed in snow or ice. What made ice cream possible was a sprinkling of chemical ingenuity. If salts are added to the ice, the salts dissolve in the slush, lower *its* freezing point, and allow it to get cold enough to freeze the sugared cream.

The effect of salts on freezing was known in the 13th-century Arab world, and that knowledge eventually made its way to Italy, where ices made from fruit were described in the early 17th century. The English term "ice cream" first appears in a 1672 document from the court of Charles II, and the first printed recipes for frozen waters and creams appear in France and Naples in the 1680s and 1690s. By the time of the American Revolution, the French had discovered that frequent stirring of the freezing mix gave a finer, less crystalline texture. They had also developed super-rich versions with 20 egg yolks per pint of cream (*glace au beurre,* "ice butter"!), and ice creams flavored with various nuts and spices, orange blossoms,

The First Recipes for Ice Cream

Neige de fleurs d'orange ("Snow of Orange Flowers")

You must take sweet cream, and put thereto two handfuls of powdered sugar, and take petals of orange flowers and mince them small, and put them in your cream . . . and put all into a pot, and put your pot in a wine cooler; and you must take ice, crush it well and put a bed of it with a handful of salt at the bottom of the cooler before putting in the pot. . . . And you must continue putting a layer of ice and a handful of salt, until the cooler is full and the pot covered, and you must put it in the coolest place you can find, and you must shake it from time to time for fear it will freeze into a solid lump of ice. It will take about two hours.

—*Nouveau confiturier,* 1682

Fromage à l'angloise (English Cheese)

Take a *chopine* [2 cups/500 ml] of sweet cream and the same of milk, half a pound of powdered sugar, stir in three egg yolks and boil until it becomes like a thin porridge; take it from the fire and pour it into your ice mould, and put it in the ice for three hours; and when it is firm, withdraw the mold, and warm it a little, in order more easily to turn out your cheese, or else dip your mould for a moment in hot water, then serve it in a compôtier.

—François Massialot, *La Nouvelle instruction pour les confitures* (1692) caramel, chocolate, tea, coffee, and even rye bread.

In America, a Food for the Masses America transformed this delicacy into a food for the masses. Ice cream making was an awkward, small-batch procedure until 1843, when a Nancy Johnson of Philadelphia patented a freezer consisting of a large bucket for the brine and a sealed cylinder containing the ice-cream mix and a mixing blade, whose shaft protruded from the top and could be cranked continuously. Five years later, William G. Young of Baltimore modified Johnson's design to make the mix container rotate in the brine for more efficient cooling. The Johnson-Young freezer allowed large quantities of fine-textured ice cream to be made with a simple, steady mechanical action.

The second fateful advance toward mass production came in the early 1850s, when a Baltimore milk dealer by the name of Jacob Fussell decided to use his seasonal surplus of cream to make ice cream, was able to charge half the going price in specialty shops, and enjoyed great success as the first large-scale manufacturer. His example caught on, so that by 1900 an English visitor was struck by the "enormous quantities" of ice cream eaten in America. Today Americans still eat substantially more ice cream than Europeans do, nearly 20 quarts/liters per person every year.

The Industrialization of Ice Cream Once ice cream became an industrial product, industry redefined it. Manufacturers could freeze their ice cream faster and colder than the handmade version, and so could produce very fine ice crystals. Smoothness of texture became the hallmark of industrial ice cream, and manufacturers accentuated it by replacing traditional ingredients with gelatin and concentrated milk solids. After World War II, they dosed ice cream with greater amounts of stabilizers to preserve its smoothness in the new and unpredictable home freezers. And price competition led to the increasing use of additives, powdered milk from surplus production, and artificial flavors and colors. So an ice cream hierarchy developed. At the top is traditional but relatively expensive ice cream; at the bottom, a lower-quality but more stable and affordable version.

The Structure and Consistency of Ice Cream

Ice Crystals, Concentrated Cream, Air Ice cream consists of three basic elements: ice crystals made of pure water, the concentrated cream that the crystals leave behind as they form from the prepared mix, and tiny air cells formed as the mix is churned during the freezing.

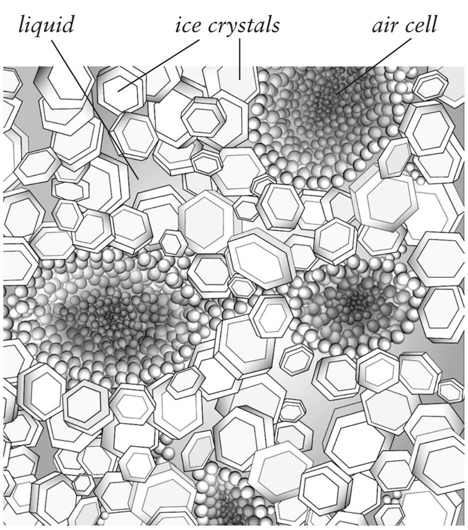
- The ice crystals form from water molecules as the mix freezes, and give ice cream its solidity; they're its backbone. And their size determines whether it is fine and smooth or coarse and grainy. But they account for only a fraction of its volume.
- The concentrated cream is what is left of the mix when the ice crystals form. Thanks to all the dissolved sugar, about a fifth of the water in the mix remains unfrozen even at 0ºF/–18ºC. The result is a very thick fluid that's about equal portions of liquid water, milk fat, milk proteins, and sugar. This fluid coats each of the many millions of ice crystals, and sticks them together—but not too strongly.
- Air cells are trapped in the ice cream mix when it's agitated during the freezing. They interrupt and weaken the matrix of ice crystals and cream, making that matrix lighter and easier to scoop and bite into. The air cells inflate the volume of the ice cream over the volume of the original mix. The increase is called *overrun,* and in a fluffy ice cream can be as much as 100%: that is, the final ice cream volume is half mix and half air. The lower the overrun, the denser the ice cream.

Balance The key to making a good ice cream is to formulate a mix that will freeze into a balanced structure of ice crystals, concentrated cream, and air. The consistency of a balanced, well made ice cream is creamy, smooth, firm, almost chewy. The smaller the proportion of water in the mix, the easier it is to make small crystals and a smooth texture. However, too much sugar and milk solids gives a heavy, soggy, syrupy result, and too much fat can end up churning into butter. Most good ice cream recipes produce a mix with a water content around 60%, a sugar content around 15%, and a milk-fat content between 10%—the minimum for commercial U.S. ice cream—and 20%.

Styles of Ice Cream Flavorings apart, there are two major styles of ice cream, and several minor ones.

- *Standard* or *Philadelphia-style* ice cream is made from cream and milk, sugar, and a few other minor ingredients. Its appeal is the richness and delicate flavor of cream itself, complemented by vanilla or by fruits or nuts.
- *French* or *custard* ice cream contains an additional ingredient: egg yolks, as many as 12 per quart/liter. The proteins and emulsifiers in egg yolk can help keep ice crystals small and the texture smooth even at relatively low milk-fat and high water levels; some traditional French ice cream mixes are a *crème anglaise* (p. 98) made with milk, not cream. A mix that contains yolks must be cooked to disperse the proteins and emulsifiers (and kill any bacteria in the raw yolks), and the resulting thickened, custard-like mix makes an ice cream with a characteristic cooked, eggy flavor.

  A distinct style of custard ice cream is the Italian *gelato,* which is typically high in butterfat as well as egg yolks, and frozen with little overrun into a very rich, dense cream. (The name simply means "frozen," and in Italy is applied to a range of frozen preparations.)
- *Reduced-fat, low-fat, and nonfat ice creams* contain progressively less fat than the 10% minimum specified in the commercial American definition of ice cream. They keep their ice crys-



Ice cream, a semisolid foam. The process of freezing the ice-cream mix forms ice crystals—solid masses of pure water—and concentrates the remaining mix into a liquid rich in sugar and milk proteins. Churning fills the mix with air bubbles, which are stabilized by layers of clustered fat globules.

The Typical Compositions of Ice Creams

With the exception of overrun and calories, the percentages shown are the percentages by weight of the ice cream.

Style	**% Milk Fat**	**% Other Milk Solids**	**% Sugar**	**% Yolk Solids (Stabilizers)**	**% Water**	**Overrun (% volume of original mix)**	**Calories per ½ c/125 ml**
Premium standard	16–20	7–8	13–16	(0.3)	64–56	20–40	240–360
Name-brand standard	12–14	8–11	13–15	(0.3)	67–60	60–90	130–250
Economy standard	10	11	15	(0.3)	64	90–100	120–150
"French" (commercial)	10–14	8–11	13–15	2	67–58	60–90	130–250
French (handmade)	3–10	7–8	15–20	6–8	69–54	0–20	150–270
Gelato	8–12	6–10	16–18	4–8	65–60	0–10	250–300
Soft-serve	3–10	11–14	13–16	(0.4)	73–60	30–60	175–190
Low-fat	2–4	12–14	18–21	(0.8)	68–61	75–90	80–135
Sherbet	1–3	1–3	26–35	(0.5)	72–59	25–50	95–140
Kulfi	7	18	5–15	—	70–60	0–20	170–230

tals small with a variety of additives, including corn syrup, powdered milk, and vegetable gums. "Soft-serve" ice cream is a reduced-fat preparation whose softness comes from being dispensed at a relatively high temperature (20–22ºF/–6ºC).

- *Kulfi,* the Indian version of ice cream that may go back to the 16th century, is made without stirring from milk boiled down to a fraction of its original volume, and therefore concentrated in texture-smoothing milk proteins and sugar. It has a strong cooked-milk, butterscotch flavor.

Generally, premium-quality ice creams are made with more cream and egg yolks than less expensive types. They also contain less air. Hefting cartons is a quick way to estimate value; there can be as much cream and sugar in an expensive pint as there is in a cheap quart, which may be up to half empty space.

Making Ice Cream There are three basic steps in making ice cream: preparing the mix, freezing it, and hardening it.

Preparing the Mix The first step is to choose the ingredients and combine them. The basic ingredients are fresh cream and milk and table sugar. A mix made of up to 17% milk fat (equal volumes of whole milk and heavy cream) and 15% table sugar (¾ cup per quart/180 gm per liter of liquid) will be smooth when frozen quickly in kitchen ice cream makers. A smooth but lower-fat ice cream can be made by making a custard-style mix with egg yolks; or by replacing some of the cream with high-protein evaporated, condensed, or powdered milk; or replacing some of the sugar with thickening corn syrup.

In commercial practice, most or all of the mix ingredients are combined, then pasteurized, a step that also helps dissolve and hydrate the ingredients. If carried out at a high enough temperature (above 170ºF/76ºC), cooking can improve the body and smoothness of the ice cream by denaturing the whey proteins, which helps minimize the size of the ice crystals. Mixes that include egg yolks are always cooked until they just thicken. Simple home mixtures of cream and sugar can be frozen uncooked and have their own fresh flavor.

Freezing Once the mix has been prepared, it's prechilled to speed the subsequent freezing. It's then frozen as rapidly as possible in a container with coolant-chilled walls. The

Freezing Ice Cream
with Flying Fortresses and Liquid Nitrogen

On March 13, 1943, the *New York Times* reported that American fliers stationed in Britain had discovered an ingenious way of making ice cream while on duty. A story titled "Flying Fortresses Double as Ice-Cream Freezers" disclosed that the airmen "place prepared ice-cream mixture in a large can and anchor it to the rear gunner's compartment of a Flying Fortress. It is well shaken up and nicely frozen by flying over enemy territory at high altitudes."

These days, a popular, spectacular, and effective method among chemistry teachers is to freeze the mix in an open bowl with a gallon or two/8–10 liters of liquid nitrogen, whose boiling point is –320ºF/–196ºC. When the liquid nitrogen is stirred in, it boils, bubbles, and chills the mix almost instantly throughout, a combination that makes a very smooth—and initially very cold!—ice cream.

mix is stirred to expose it evenly to the cold walls, to incorporate some air, and above all to produce a smooth texture. Slow cooling of an unstirred mix—"quiescent cooling"—causes the formation of relatively few ice crystals that grow to a large size, grow together into clumps, and give a coarse, icy texture. Rapid cooling with stirring causes the quick production of many "seed" crystals which, because they share the available water molecules among themselves, cannot grow as large as a smaller population could; the agitation also helps prevent several crystals from growing into each other and forming a cluster that the tongue might notice. And many small crystals give a smooth, velvety consistency.

Hardening Hardening is the last stage in making ice cream. When the mix becomes thick and difficult to stir, only about half of its water has frozen into ice crystals. Agitation is then stopped, and the ice cream is finished with a period of quiescent freezing, during which another 40% of its water migrates onto existing ice crystals, leaving the various solid components less lubricated. If hardening is slow, some ice crystals take up more water than others and coarsen the texture. Hardening can be accelerated by dividing the newly frozen ice cream into several small containers whose greater surface area will release heat faster than one large container.

Storing and Serving Ice Cream Ice cream is best stored as cold as possible, at 0ºF/–18ºC or below, to preserve its smoothness. The inevitable coarsening during storage is due to repeated partial thawings and freezings, which melt the smallest ice crystals completely and deposit their water molecules on ever fewer, ever larger crystals. The lower the storage temperature, the slower this coarsening process.

The ice cream surface suffers in two ways during storage: its fat absorbs odors from the rest of the freezer compartment, and can be damaged and go rancid when dried out by the freezer air. These problems can be prevented simply by pressing plastic wrap directly into the surface, being careful not to leave air pockets.

Ideally, ice cream should be allowed to warm up from 0ºF before being served. At 8–10ºF/–13ºC, it doesn't numb the tongue and taste buds as much, and it contains more liquid water, which softens the texture. At 22ºF/–6ºC—the typical temperature of soft-serve ice cream—half of the water is in liquid form.

FRESH FERMENTED MILKS AND CREAMS

One of the remarkable qualities of milk is that it invites its own preservation. It can spontaneously foster a particular group of microbes that convert its sugar into acid, and thereby preserve it for some time from spoiling or harboring disease. At the same time, the microbes also change the milk's texture and flavor in desirable ways. This benign transformation, or *fermentation,* doesn't happen all the time, but it happened often enough that milks fermented by bacteria became important among all dairying peoples. Yogurt and soured creams remain widely popular to this day.

Why this fortunate fermentation? It's a combination of milk's unique chemistry, and a group of microbes that were ready to exploit this chemistry long before mammals and milk arrived on earth. The *lactic acid bacteria* are what make possible the variety of fermented dairy products.

Lactic Acid Bacteria

Milk is rich in nutrients, but its most readily tapped energy source, lactose, is a sugar found almost nowhere else in nature. This means that not many microbes have the necessary digestive enzymes at the ready. The elegantly simple key to the success of the milk bacteria is that they specialize in digesting lactose, and they extract energy from lactose by breaking it down to lactic acid. Then they release the lactic acid into the milk, where it accumulates and retards the growth of most other microbes, including those that cause human disease. They also make some antibacterial substances, but their main defense is a pleasantly puckery tartness, one that also causes the casein proteins to gather together in semisolid curds (p. 20) and thicken the milk.

There are two major groups of lactic acid bacteria. The small genus *Lactococcus* (a combination of the Latin for "milk" and "sphere") is found primarily on plants (but it's a close relative of *Streptococcus,* whose members live mainly on animals and cause a number of human diseases!). The 50-odd members of the genus *Lactobacillus* ("milk" and "rod") are more widespread in nature. They're found both on plants and in animals, including the stomach of milk-fed calves and the human mouth, digestive tract, and vagina; and their clean living generally benefits our insides (see box, p. 47).

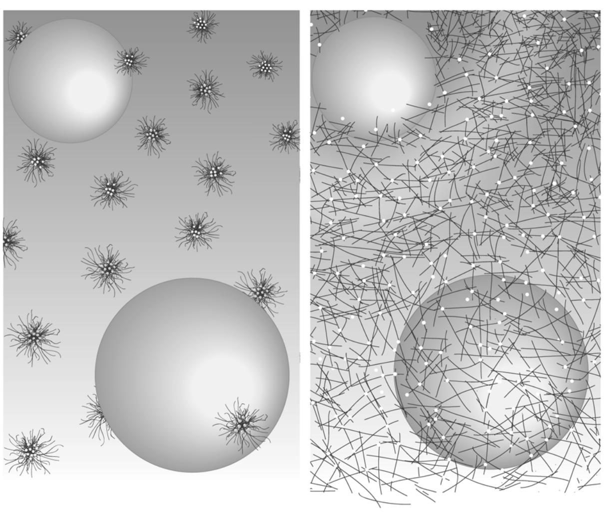
The bacteria responsible for the major fermented products were identified around 1900, and pure cultures of individual strains became available then. Nowadays, few dairies leave their fermentations to chance. Where traditional spontaneously fermented products may involve a dozen or more different microbes, the industrial versions are usually limited to two or three. This biological narrowing may affect flavor, consistency, and health value.

Families of Fresh Fermented Milks

Unlike most cheeses (p. 51), which undergo several stages of manipulation and continue to evolve for weeks or months, fresh fermented milks are usually finished and ready for eating within hours or days. A recent encyclopedia catalogued several hundred different kinds! Most of them originated in western Asia, eastern Europe, and Scandinavia, and have been carried across the globe by countless emigrants, many of whom dipped a cloth in their family's culture, dried it gently, and guarded it until they could moisten it in the milk of their new home.

The handful of fresh fermented milks familiar in the West, yogurt and soured creams and buttermilk, represent two major families that developed from the dairying habits of peoples in two very different climates.

Yogurt and its relatives are native to a broad and climatically warm area of central and southwest Asia and the Middle East, an



The curdling of milk by lactic acid bacteria. As the bacteria ferment lactose and produce lactic acid, the increasingly acid conditions cause the normal bundled micelles of casein proteins (left) *to fall apart into separate casein molecules, and then rebond to each other* (right). *This general rebonding forms a continuous meshwork of protein molecules that traps the liquid and fat globules in small pockets, and turns the fluid milk into a fragile solid.*

Traditional Fresh Fermented Milks and Creams

Product	Region	Microbes	Fermentation Temperature, Time	Acidity	Characteristics
Yogurt	Middle East to India	*Lactobacillus delbrueckii*, *Streptococcus salivarius* (in rural areas, assorted lactococci and lactobacilli)	106–114°F/41–45°C, 2–5 hrs, or 86°F/30°C, 6–12 hrs	1–4%	Tart, semisolid, smooth; green aroma
Buttermilk	Eurasia	*Lactococcus lactis*, *Leuconostoc mesenteroides*	72°F/22°C, 14–16 hrs	0.8–1.1%	Tart, thickened liquid; buttery aroma
Crème fraîche	Europe	*Lactococcus lactis*, *Leuconostoc mesenteroides*	68°F/20°C, 15–20 hrs	0.2–0.8%	Mildly tart and thickened; buttery aroma
Sour cream	Europe	*Lactococcus lactis*, *Leuconostoc mesenteroides*	72°F/22°C, 16 hrs	0.8%	Mildly tart, semisolid; buttery aroma
Ropy milks	Scandinavia	*Lactococcus lactis*, *Leuconostoc mesenteroides* (*Geotrichum* mold)	68°F/20°C, 18 hrs	0.8%	Mildly tart, semisolid, slimy; buttery aroma
Koumiss	Central Asia	Lactobacilli, yeasts	80°F/27°C, 2–5 hrs plus cool aging	0.5–1%	Mildly tart, thickened liquid; effervescent, 0.7–2.5% alcohol
Kefir	Central Asia	Lactococci, Lactobacilli, *Acetobacter*, yeasts	68°F/20°C, 24 hrs	1%	Tart, thickened liquid; effervescent, 0.1% alcohol

area that includes the probable home of dairying, and where some peoples still store milk in animal stomachs and skins. The lactobacilli and streptococci that produce yogurt are "thermophilic," or heat-loving species that may have come from the cattle themselves. They're distinguished by their ability to grow rapidly and synergistically at temperatures up to 113ºF/45ºC, and to generate high levels of preservative lactic acid. They can set milk into a very tart gel in just two or three hours.

Sour cream, crème fraîche, and buttermilk are indigenous to relatively cool western and northern Europe, where milk spoils more slowly and was often left overnight to separate into cream for buttermaking. The lactococci and *Leuconostoc* species that produce them are "mesophilic," or moderate-temperature lovers that probably first got into milk from particles of pasturage on the cows' udders. They prefer temperatures around 85ºF/30ºC but will work well below that range, and develop moderate levels of lactic acid during a slow fermentation lasting 12 to 24 hours.

Yogurt

Yogurt is the Turkish word for milk that has been fermented into a tart, semisolid mass; it comes from a root meaning

The Health Benefits of Fermented Milks

The bacteria in dairy products may do more for us than just predigest lactose and create flavor. Recent research findings lend some support to the ancient and widespread belief that yogurt and other cultured milks can actively promote good health. Early in the 20th century, the Russian Nobelist Ilya Metchnikov (who discovered that white blood cells fight bacterial infection) gave a scientific rationale to this belief, when he proposed that the lactic acid bacteria in fermented milks eliminate toxic microbes in our digestive system that otherwise shorten our lives. Hence Dr. James Empringham's charming title of 1926: *Intestinal Gardening for the Prolongation of Youth.*

Metchnikov was prescient. Research over the last couple of decades has established that certain lactic acid bacteria, the Bifidobacteria, are fostered by breast milk, do colonize the infant intestine, and help keep it healthy by acidifying it and by producing various antibacterial substances. Once we're weaned onto a mixed diet, the Bifidobacterial majority in the intestine recedes in favor of a mixed population of *Streptococcus, Staphylococcus, E. coli,* and yeasts. The standard industrial yogurt and buttermilk bacteria are specialized to grow well in milk and can't survive inside the human body. But other bacteria found in traditional, spontaneously fermented milks—*Lactobacillus fermentum, L. casei,* and *L. brevis,* for example—as well as *L. plantarum* from pickled vegetables, and the intestinal native *L. acidophilus,* do take up residence in us. Particular strains of these bacteria variously adhere to and shield the intestinal wall, secrete antibacterial compounds, boost the body's immune response to particular disease microbes, dismantle cholesterol and cholesterol-consuming bile acids, and reduce the production of potential carcinogens.

These activities may not amount to prolonging our youth, but they're certainly desirable! Increasingly, manufacturers are adding "probiotic" Lactobacilli and even Bifidobacteria to their cultured milk products, and note that fact on the label. Such products, approximations of the original fermented milks that contained an even more diverse bacterial flora, allow us to plant our inner gardens with the most companionable microbes we're currently aware of.

"thick." Essentially the same product has been made for millennia from eastern Europe and North Africa across central Asia to India, where it goes by a variety of names and is used for a variety of purposes: it's eaten on its own, diluted into drinks, mixed into dressings, and used as an ingredient in soups, baked goods, and sweets.

Yogurt remained an exotic curiosity in Europe until early in the 20th century, when the Nobel Prize–winning immunologist Ilya Metchnikov connected the longevity of certain groups in Bulgaria, Russia, France, and the United States with their consumption of fermented milks, which he theorized would acidify the digestive tract and prevent pathogenic bacteria from growing (see box, p. 47). Factory-scale production and milder yogurts flavored with fruit were developed in the late 1920s, and broader popularity came in the 1960s with Swiss improvements in the inclusion of flavors and fruits and the French development of a stable, creamy stirred version.

The Yogurt Symbiosis By contrast to the complex and variable flora of traditional yogurts, the industrial version is reduced to the essentials. Standard yogurt contains just two kinds of bacteria, *Lactobacillus delbrueckii* subspecies *bulgaricus,* and *Streptococcus salivarius* subspecies *thermophilus*. Each bacterium stimulates the growth of the other, and the combination acidifies the milk more rapidly than either partner on its own. Initially the streptococci are most active. Then as the acidity exceeds 0.5%, the acid-sensitive streptococci slow down, and the hardier lactobacilli take over and bring the final acidity to 1% or more. The flavor compounds produced by the bacteria are dominated by acetaldehyde, which provides the characteristic refreshing impression of green apples.

Making Yogurt There are two basic stages in yogurt making: preparing the milk by heating and partly cooling it; and fermenting the warm milk.

The Milk Yogurt is made from all sorts of milk; sheep and goat were probably the first. Reduced-fat milks make especially firm yogurt because manufacturers mask their lack of fat by adding extra milk proteins, which add density to the acid-coagulated protein network. (Manufacturers may also add gelatin, starch, and other stabilizers to help prevent separation of whey and curd from physical shocks during transportation and handling.)

Heating the Milk Traditionally the milk for yogurt was given a prolonged boiling to concentrate the proteins and give a firmer texture. Today, manufacturers can boost protein content by adding dry milk powder, but they still cook the milk, for 30 minutes at 185ºF/85ºC or at 195ºF/90ºC for 10 minutes. These treatments improve the consistency of the yogurt by denaturing the whey protein lactoglobulin, whose otherwise unreactive molecules then participate by clustering on the surfaces of the casein particles (p. 20). With the helpful interference of the lactoglobulins, the casein particles can only bond to each other at a few spots, and so gather not in clusters but in a fine matrix of chains that is much better at retaining liquid in its small interstices.

The Fermentation Once the milk has been heated, it's cooled down to the desired fermentation temperature, the bacteria are added (often in a portion of the previous batch), and the milk kept warm until it sets. The fermentation temperature has a strong influence on yogurt consistency. At the maximum temperature well tolerated by the bacteria, 104–113ºF/40–45ºC, the bacteria grow and produce lactic acid rapidly, and the milk proteins gel in just two or three hours; at 86ºF/30ºC, the bacteria work far more slowly, and the milk takes up to 18 hours to set. Rapid gelling produces a relatively coarse protein network whose few thick strands give it firmness but also readily leak whey; slow gelling produces a finer, more delicate, more intricately branched network whose individual strands are weaker but whose smaller pores are better at retaining the whey.

Frozen Yogurt Frozen yogurt became popular in the 1970s and '80s as a low-fat, "healthy" alternative to ice cream. In fact, frozen yogurt is essentially ice milk whose mix includes a small dose of yogurt; the standard proportion is 4 to 1. Depending on the mixing procedure, the yogurt bacteria may survive in large numbers or be largely eliminated.

Soured Creams and Buttermilk, Including Crème Fraîche

Before the advent of the centrifugal separator, butter was made in western Europe by allowing raw milk to stand overnight or longer, skimming off the cream that rose to the top, and churning the cream. During the hours of gravity separation, bacteria would grow spontaneously in the milk and give the cream and the butter made from it a characteristic aroma and tartness.

"Cream cultures" is a convenient shorthand for products that are now intentionally seeded with these same bacteria, which are various species of *Lactococcus* and *Leuconostoc,* and have three important characteristics. They grow best at moderate temperatures, well below the typical temperature of yogurt fermentation; they're only moderate acid-producers, so the milks and creams they ferment never get extremely sour; and certain strains have the ability to convert a minor milk component, citrate, into a warmly aromatic compound called diacetyl that miraculously complements the flavor of butterfat. It's fascinating that this single bacterial product is so closely associated with the flavor of butter that all by itself, diacetyl makes foods taste buttery: even chardonnay wines (p. 730). To accentuate this flavor note, manufacturers sometimes add citrate to the milk or cream before fermentation, and they ferment in the cool conditions that favor diacetyl production.

Crème Fraîche Crème fraîche is a versatile preparation. Thick, tart, and with an aroma that can be delicately nutty or buttery, it is a wonderful complement to fresh fruit, to caviar, and to certain pastries. And thanks to its high fat and correspondingly low protein content, it can be cooked in a sauce or even boiled down without curdling.

In France today, crème fraîche means cream with 30% fat that has been pasteurized at moderate temperatures, not UHT pasteurized (p. 22) or sterilized. (*Fraîche* means "cool" or "fresh.") It may, however, be either liquid (*liquide, fleurette*) or thick (*épaisse*). The liquid version is unfermented and has an official refrigerated shelf life of 15 days. The thick version is fermented with the typical cream culture for 15 to 20 hours, and has a shelf life of 30 days. As with all fermented milks, the thickening is an indication that the product has reached a certain acidity (0.8%, pH 4.6) and so a distinct tartness. Commercial American crème fraîche is made essentially as the French fermented version is, though some manufacturers add a small amount of rennet for a thicker consistency. A distinctly buttery flavor is found in products made with Jersey and Guernsey milks (rich in citrate) and with diacetyl-producing strains of bacteria.

Making Crème Fraîche in the Kitchen A home version of crème fraîche can be made by adding some cultured buttermilk or sour cream, which contain cream-culture bacteria, to heavy cream (1 tablespoon per cup/15 ml per 250 ml), and letting it stand at a cool room temperature for 12 to 18 hours or until thick.

Sour Cream Sour cream is essentially a leaner, firmer, less versatile version of crème fraîche. At around 20% milk fat, it contains enough protein that cooking temperatures will curdle it. Unless it is used to enrich a dish just before serving, then, it will give a slightly grainy appearance and texture. Sour cream is especially prominent in central and eastern Europe, where it has traditionally been added to soups and stews (goulash, borscht). Immigrants brought a taste for it to American cities in the 19th century, and by the middle of the 20th it had become fully naturalized as a base for dips and salad dressings, a topping for baked potatoes, and an ingredient in cakes. American sour cream is heavier-bodied than the European original thanks to the practice of passing the cream through a homogenizer twice before culturing it. A small dose of rennet is sometimes added with the bacteria; this enzyme causes the casein proteins to coagulate into a firmer gel.

A nonfermented imitation called "acidified sour cream" is made by coagulating the cream with pure acid. "Sour creams" labeled "low-fat" and "nonfat" replace butterfat with starch, plant gums, and dried milk protein.

Buttermilk Most "buttermilk" sold in the United States is not buttermilk at all. True buttermilk is the low-fat portion of milk or cream remaining after it has been churned to make butter. Traditionally, that milk or cream would have begun to ferment before churning, and afterwards the buttermilk would continue to thicken and develop flavor. With the advent of centrifugal cream separators in the 19th century, buttermaking produced "sweet" unfermented buttermilk, which could be sold as such or cultured with lactic bacteria to develop the traditional flavor and consistency. In the United States, a shortage of true buttermilk shortly after World War II led to the success of an imitation, "cultured buttermilk," made from ordinary skim milk and fermented until acid and thick.

What's the difference? True buttermilk is less acid, subtler and more complex in flavor, and more prone to off-flavors and spoilage. Its remnants of fat globule membranes are rich in emulsifiers like lecithin, and make it especially valuable for preparing smooth, fine-textured foods of all kinds, from ice cream to baked goods. (Its excellence for emulsifying led to the Pennsylvania Dutch using it as a base for red barn paint!) Cultured buttermilk is useful too; it imparts a rich, tangy flavor and tenderness to griddle cakes and many baked goods.

U.S. "cultured buttermilk" is made by giving skim or low-fat milk the standard yogurt heat treatment to produce a finer protein gel, then cooling it and fermenting it with cream cultures until it gels. The gelled milk is cooled to stop the fermentation and gently agitated to break the curd into a thick but smooth liquid. "Bulgarian buttermilk" is a version of cultured buttermilk in which the cream cultures are supplemented or replaced by yogurt cultures, and fermented at a higher temperature to a higher acidity. It's noticeably more tart and gelatinous, with the apple-like sharpness typical of yogurt.

Ropy Scandinavian Milks

A distinctive subfamily among the cream cultures are the "ropy" milks of Scandinavia, so-called because they're more than stringy: lift a spoonful of Finnish *viili,* Swedish *långfil,* or Norwegian *tättemjölk,* and the rest of the bowl follows it into the air. Some ropy milks are so cohesive that they're cut with a knife. This consistency is created by particular strains of cream culture bacteria that produce long strands of starch-like carbohydrate. The stretchy carbohydrate absorbs water and sticks to casein particles, so manufacturers are using ropy strains of *Streptococcus salivarius* as natural stabilizers of yogurt and other cultured products.

Cooking with Fermented Milks

Most cultured milk products are especially susceptible to curdling when made into sauces or added to other hot foods. Fresh milk and cream are relatively stable, but the extended heat treatment and high acidity characteristic of cultured products have already caused some protein coagulation. Anything the cook does to push this coagulation further will cause the protein network to shrink and squeeze out some of the whey and produce distinct white particles—protein curds—floating in the thinned liquid. Heat, salt, additional acid, and vigorous stirring can all cause curdling. The key to maintaining a smooth texture is gentleness. Heat gradually and moderately, and stir slowly.

There is a common misconception that crème fraîche is uniquely immune to curdling. It's true that while yogurt, sour cream, and buttermilk all will curdle if they get anywhere near the boil, crème fraîche can be boiled with impunity. But this versatility has nothing to do with fermentation: it's a simple matter of fat content. Heavy cream, at 38 to 40% fat, has so little protein that it doesn't form noticeable curds (p. 29).

CHEESE

Cheese is one of the great achievements of humankind. Not any cheese in particular, but cheese in its astonishing multiplicity, created anew every day in the dairies of the world. Cheese began as a simple way of concentrating and preserving the bounty of the milking season. Then the attentiveness and ingenuity of its makers slowly transformed it into something more than mere physical nourishment: into an intense, concentrated expression of pastures and animals, of microbes and time.

The Evolution of Cheese

Cheese is a modified form of milk that is more concentrated, more durable, and more flavorful food than milk is. It's made more concentrated by curdling milk and removing much of its water. The nutritious curds of protein and fat are made more durable

Unusual Fermented Milks: Koumiss and Kefir

Because milk contains an appreciable amount of the sugar lactose, it can be fermented like grape juice and other sugary fluids into an alcoholic liquid. This fermentation requires unusual lactose-fermenting yeasts (species of *Saccharomyces, Torula, Candida,* and *Kluyveromyces*). For thousands of years, the nomads of central Asia have made *koumiss* from mare's milk, which is especially rich in lactose, and this tart, effervescent drink, with 1–2% alcohol and 0.5–1% acid, remains very popular there and in Russia. Other European and Scandinavian peoples have made alcoholic products from other milks, as well as sparkling "wine" from whey.

Another remarkable fermented milk little known in the West is *kefir,* which is most popular in the Caucasus and may well have originated there. Unlike other fermented milks, in which the fermenting microbes are evenly dispersed, kefir is made by large, complex particles known as kefir grains, which house a dozen or more kinds of microbes, including lactobacilli, lactococci, yeasts, and vinegar bacteria. This symbiotic association grows at cool room temperatures to produce a tart, slightly alcoholic, effervescent, creamy product.

by the addition of acid and salt, which discourage the growth of spoilage microbes. And they're made more flavorful by the controlled activity of milk and microbe enzymes, which break the protein and fat molecules apart into small flavorful fragments.

The long evolution of cheese probably began around 5,000 years ago, when people in warm central Asia and the Middle East learned that they could preserve naturally soured, curdled milk by draining off the watery whey and salting the concentrated curds. At some point they also discovered that the texture of the curd became more pliable and more cohesive if the curdling took place in an animal stomach or with pieces of stomach in the same container. These first cheeses may have resembled modern brine-cured feta, which is still an important cheese type in the eastern Mediterranean and the Balkans. The earliest good evidence of cheesemaking known to date, a residue found in an Egyptian pot, dates from around 2300 BCE.

The Ingredient Essential to Diverse Cheeses: Time This basic technique of curdling milk with the help of the stomach extract now called rennet, then draining and brining the curds, was eventually carried west and north into Europe. Here people gradually discovered that curds would keep well enough in these cooler regions with much milder treatments: a less puckery souring and only a modest brining or salting. This was the discovery that opened the door to the great diversification of cheeses, because it introduced a fifth ingredient after milk, milk bacteria, rennet, and salt: time. In the presence of moderate acidity and salt, cheese became a hospitable medium for the continuing growth and activity of a variety of microbes and their enzymes. In a sense, cheese came to life. It became capable of pronounced development and change; it entered the cyclical world of birth, maturation, and decline.

When were modern cheeses born? We don't really know, but it was well before Roman times. In his *Rei rusticae* ("On Rustic Matters," about 65 CE), Columella describes at length what amounts to standard cheesemaking practice. The curdling was done with rennet or various plant fluids. The whey was pressed out, the curds sprinkled with salt, and the fresh cheese put in a shady place to harden. Salting and hardening were repeated, and the ripe cheese was then washed, dried, and packed for storage and shipping. Pliny, who also wrote in the first century, said that Rome most esteemed cheeses from its provincial outposts, especially Nîmes in southern France, and the French and Dalmatian Alps.

The Growth of Diversity During the 10 or 12 centuries after Rome's strong rule, the art of cheesemaking progressed in the feudal estates and monasteries, which worked

Cheeses as Artifacts

Behind every cheese there is a pasture of a different green under a different sky: meadows encrusted with salt that the tides of Normandy deposit every evening; meadows perfumed with aromas in the windy sunlight of Provence; there are different herds, with their shelters and their movements across the countryside; there are secret methods handed down over the centuries. This shop is a museum: Mr. Palomar, visiting it, feels as he does in the Louvre, behind every displayed object the presence of the civilization that gave it form and takes form from it.

—Italo Calvino, *Palomar,* 1983

steadily at settling in forested areas or mountain meadows and clearing the land for grazing. These widely dispersed communities developed their cheesemaking techniques independently to suit their local landscape, climate, materials, and markets. Small, perishable soft cheeses, often made from the milk of a few household animals, were consumed locally and quickly and could only be sent to nearby towns. Large hard cheeses required the milk of many animals and were often made by cooperatives (the Gruyère *fruiteries* began around 1200); they kept indefinitely and could be transported to market from distant regions. The result was a remarkable diversity of traditional cheeses, which number from 20 to 50 in most countries and several hundred in France alone, thanks to its size and range of climates.

Charlemagne Learns to Eat Moldy Cheese

During the Middle Ages, when cheese was evolving into a finely crafted food, even an emperor of France had to learn a thing or two about how to appreciate it. About 50 years after Charlemagne's death in 814, an anonymous monk at the monastery of Saint Gall wrote a biography of him that includes this fascinating anecdote (slightly modified from *Early Lives of Charlemagne*, transl. A. J. Grant, 1922). Charlemagne was traveling, and found himself at a bishop's residence at dinnertime.

> Now on that day, being the sixth day of the week, he was not willing to eat the flesh of beast or bird. The bishop, being by reason of the nature of the place unable to procure fish immediately, ordered some excellent cheese, white with fat, to be placed before him. Charles . . . required nothing else, but taking up his knife and throwing away the mold, which seemed to him abominable, he ate the white of the cheese. Then the bishop, who was standing nearby like a servant, drew close and said "Why do you do that, lord Emperor? You are throwing away the best part." On the persuasion of the bishop, Charles . . . put a piece of the mold in his mouth, and slowly ate it and swallowed it like butter. Then, approving the bishop's advice, he said "Very true, my good host," and he added, "Be sure to send me every year to Aix two cartloads of such cheeses."

The word I've translated as "mold" is *aerugo* in the Latin: literally, "the rust of copper." The cheese isn't named, and some writers have deduced that it was a Brie, which then had an external coat of gray-green mold, much the same color as weathered copper. But I think it was probably more like Roquefort, a sheep's-milk cheese veined internally with blue-green mold. The rest of the anecdote fits a large, firm, internally ripened cheese better than a thin, soft Brie. It also marks what may have been the first appointment of an official cheese affineur!

> The bishop was alarmed at the impossibility of the task and . . . rejoined: "My lord, I can procure the cheeses, but I cannot tell which are of this quality and which of another. . . ." Then Charles . . . spoke thus to the bishop, who from childhood had known such cheeses and yet could not test them. "Cut them in two," he said, "then fasten together with a skewer those that you find to be of the right quality and keep them in your cellar for a time and then send them to me. The rest you may keep for yourself and your clergy and family."

Cheeses of Reputation The art of cheesemaking had progressed enough by late medieval times to inspire connoisseurship. The French court received shipments from Brie, Roquefort, Comté, Maroilles, and Geromé (Münster). Cheeses made near Parma in Italy and near Appenzell in Switzerland were renowned throughout Europe. In Britain, Cheshire cheese was famous by Elizabethan times, and Cheddar and Stilton by the 18th century. Cheese played two roles: for the poor, fresh or briefly ripened types were staple food, sometimes called "white meat," while the rich enjoyed a variety of aged cheeses as one course of their multicourse feasts. By the early 19th century, the French gastronome Brillat-Savarin found cheese to be an aesthetic necessity: he wrote that "a dessert without cheese is like a beautiful woman who is missing an eye." The golden age of cheese was probably the late 19th and early 20th centuries, when the art was fully developed, local styles had developed and matured, and the railroads brought country products to the city while they were still at their best.

Modern Decline The modern decline of cheesemaking has its roots in that same golden age. Cheese and butter factories were born in the United States, a country with no cheesemaking tradition, just 70 years after the Revolution. In 1851, an upstate New York dairy farmer named Jesse Williams agreed to make cheese for neighboring farms, and by the end of the Civil War there were hundreds of such "associated" dairies, whose economic advantages brought them success throughout the industrialized world. In the 1860s and '70s, pharmacies and then pharmaceutical companies began mass-producing rennet. At the turn of the century scientists in Denmark, the United States, and France brought more standardization in the form of pure microbial cultures for curdling and ripening cheese, which had once been accomplished by the local, complex flora of each cheesemaker's dairy.

The crowning blow to cheese diversity and quality was World War II. In continental Europe, agricultural lands became battlefields, and dairying was devastated. During the prolonged recovery, quality standards were suspended, factory production was favored for its economies of scale and ease of regulation, and consumers were grateful for any approximation of the prewar good life. Inexpensive standardized cheese rose to dominance. Ever since, most cheese in Europe and the United States has been made in factories. Even in France, which in 1973 established a certification program ("*Fromage appellation d'origine contrôlée*") to indicate that a cheese has been made by traditional methods and in the traditional area of production, less than 20% of the total national production qualifies. In the United States, the market for *process cheese,* a mixture of aged and fresh cheeses blended with emulsifiers and repasteurized, is now larger than the market for "natural" cheese, which itself is almost exclusively factory-made.

At the beginning of the 21st century, most cheese is an industrial product, an expression not of diverse natural and human particulars, but of the monolithic imperatives of standardization and efficient mass production. Industrial cheese also requires great ingenuity, has its economic merits, and suits its primary role as an ingredient in fast-food sandwiches, snacks, and prepared foods (a role that doubled U.S. per capita cheese consumption between 1975 and 2001). But in its own way, industrial cheese is a throwback to primitive cheese, a simplified food that could be and is made anywhere, and that tastes of nowhere in particular.

The Revival of Tradition and Quality Though finely crafted cheeses will always be a minor part of modern dairy production, recent years have brought modest signs of hope. The postwar era and its economic limitations have faded. Some European countries have seen a revival of appreciation for traditional cheeses, and air travel has brought them to the attention of an ever-growing number of food lovers. Once "white meat" for the rural poor, they are now pricey treats for the urban middle class. In the United States, a few small producers blend respect for tradition with 21st-century understanding, and make superb cheeses of their own. For enthusiasts willing to seek them out, the world still offers delightful expressions of this ancient craft.

The Ingredients of Cheese

The three principal ingredients of cheese are milk, rennet enzymes that curdle the milk, and microbes that acidify and flavor the milk. Each strongly influences the character and quality of the final cheese.

Milks Cheese is milk concentrated five- to tenfold by the removal of water; so the basic character of the milk defines the basic character of the cheese. Milk character is in turn determined by the kind of animal that produces it, what the animal eats, the microbes that inhabit the milk, and whether it is raw or pasteurized.

Species The milks of cows, sheep, and goats taste different from each other (p. 21), and their cheeses do too. Cow's milk is more neutral than other milks. Sheep and buffalo milk have relatively high fat and protein contents and therefore make richer cheeses. Goat's milk has a relatively low proportion of curdle-able casein and usually produces a crumbly, less cohesive curd compared to other milks.

Breed During the spread of cheesemaking in the Middle Ages, hundreds of different dairy animal varieties were bred to make the best use of local pasturage. The Brown Swiss is thought to go back several thousand years. Today, most of these locally adapted breeds have been replaced by the omnipresent black-and-white Holstein or Friesian, bred to maximize the milk it yields on standardized feed. Traditional breeds produce a lower volume of milk, but a milk richer in protein, fat, and other desirable cheese constituents.

Feed: The Influence of the Seasons Today most dairy animals are fed year-round on silage and hay made from just a few fodder crops (alfalfa, maize). This standard regimen produces a standard, neutral milk that can be made into very good cheese. However, herds let out to pasture to eat fresh greenery and flowers give milk of greater aromatic complexity that can make extraordinary cheese. Thanks to newly sensitive analytical instruments, dairy chemists have recently verified what connoisseurs have known for centuries: an animal's diet influences its milk and the cheese made from it. French studies of alpine Gruyère found a larger number of flavor compounds in cheeses made during summer pasturage compared to winter stable feeding, and more herbaceous and floral terpenes and other aromatics (p. 273) in mountain cheeses than cheeses from the high plateaus, which in turn have more than cheeses from the plains (alpine meadows have more diverse vegetation than the grassy lowlands).

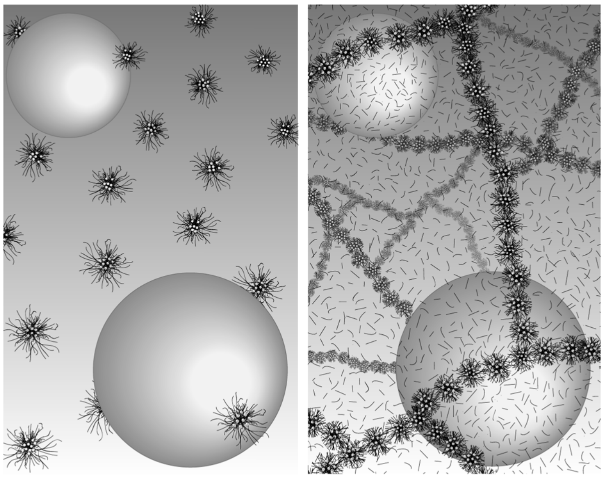
Like fruits, cheeses made from pasture-fed animals are seasonal. The season depends on the local climate—the summer is green in the Alps, the winter in California—and how long it takes a particular cheese to mature. Cheeses made from pasturage are generally recognizable by their deeper yellow color, due to the greater content of carotenoid pigments in fresh vegetation (p. 267). (Bright orange cheeses have been dyed.)

Pasteurized and Raw Milks In modern cheese production, the milk is almost always pasteurized to eliminate disease and spoilage bacteria. This is really a practical necessity in industrial cheesemaking, which requires that milk be pooled and stored from many farms and thousands of animals. The risk of contamination—which only takes one diseased cow or dirty udder—is too great. Since the late 1940s, the U.S. Food and Drug Administration has required that any cheese made from unpasteurized, "raw" milk must be aged a minimum of 60 days at a temperature above 35°F/2°C, conditions that are thought to eliminate whatever pathogens might have been in the milk; and since the early 1950s it has also banned the import of raw-milk cheeses aged less than 60 days. This means that soft cheeses made with raw milk are essentially contraband in the United States. The World Health Organization has considered recommending a complete ban on the production of raw-milk cheeses.

Of course until barely a century ago, nearly all cheeses were made in small batches with raw milk, fresh from the udders of small herds whose health was more easily monitored. And French, Swiss, and Italian regulations actually *forbid* the use of pasteurized milk for the traditional production of a number of the world's greatest cheeses, including Brie, Camembert, Comté, Emmental, Gruyère, and Parmesan. The reason is that pasteurization kills useful milk bacteria, and inactivates many of the milk's own enzymes. It thus eliminates two of the four or five sources of flavor development during ripening, and prevents traditional cheeses from living up to their own standards of excellence.

Pasteurization is no guarantee of safety, because the milk or cheese can be contaminated during later processing. Nearly all outbreaks of food poisoning from milk or cheese in recent decades have involved pasteurized products. It will be genuine progress when public health officials help ambitious cheesemakers to ensure the safety of raw-milk cheeses, rather than making rules that restrict consumer choice without significantly reducing risk.

The Key Catalyst: Rennet The making and use of rennet was humankind's first venture in biotechnology. At least 2,500 years ago, shepherds began to use pieces of the first stomach of a young calf, lamb, or goat to curdle milk for cheese; and sometime later they began to make a brine extract from the stomach. That extract was the world's first semipurified enzyme. Now, by means of genetic engineering, modern biotechnology produces a pure version of the same calf enzyme, called *chymosin,* in a bacterium, a mold, and a yeast. Today, most cheese in the United States is made with these engineered "vegetable rennets," and less than a quarter with traditional rennet from calf stomach (which is often required for traditional European cheeses).



The curdling of milk by the rennet enzyme chymosin. The bundled micelles of casein in milk are kept separate from each other by electrically charged micelle components that repel each other (left). *Chymosin selectively trims away these charged kappa-caseins, and the now uncharged micelles bond to each other to form a continuous meshwork* (right). *The liquid milk coagulates into a moist solid.*

The Curdling Specialist Traditional rennet is made from the fourth stomach or abomasum of a milk-fed calf less than 30 days old, before chymosin is replaced by other protein-digesting enzymes. The key to rennet's importance in cheesemaking is chymosin's specific activity. Where other enzymes attack most proteins at many points and break them into many pieces, chymosin effectively attacks only one milk protein, and at just one point. Its target is the negatively charged kappa-casein (p. 19) that repels individual casein particles from each other. By clipping these pieces off, chymosin allows the casein particles to bond to each other and form a continuous solid gel, the curd.

Since plain acidity alone causes milk to curdle, why do cheesemakers need rennet at all? There are two reasons. First, acid disperses the casein micelle proteins and their calcium glue before it allows the proteins to come together, so some casein and most of the calcium are lost in the whey, and the remainder forms a weak, brittle curd. By contrast, rennet leaves the micelles mostly intact and causes each to bond to several others into a firm, elastic curd. Second, the acidity required to curdle casein is so high that flavor-producing enzymes in the cheese work very slowly or not at all.

Cheese Microbes Cheeses are decomposed and recomposed by a colorful cast of microbes, perhaps a handful in most modern cheeses made with purified cultures, but dozens in some traditional cheeses made with a portion of the previous batch's starter.

Starter Bacteria First there are the lactic acid bacteria that initially acidify the milk, persist in the drained curd, and generate much of the flavor during the ripening of many semihard and hard cheeses, including Cheddar, Gouda, and Parmesan. The numbers of live *starter* bacteria in the curd often drop drastically during cheesemaking, but their enzymes survive and continue to work for months, breaking down proteins into savory amino acids and aromatic byproducts (see box, p. 62). There are two broad groups of starters: the moderate-temperature lactococci that are also used to make cultured creams, and the heat-loving lactobacilli and streptococci that are also used to make yogurt (p. 48). Most cheeses are acidified by the mesophilic group, while the few that undergo a cooking step—mozzarella, the alpine and Italian hard cheeses—are acidified by thermophiles that can survive and continue to contribute flavor. Many Swiss and Italian starters are still only semidefined mixtures of heat-loving milk bacteria, and are made the old-fashioned way, from the whey of the previous batch.

True "Vegetable Rennets" from Thistle Flowers

It has been known at least since Roman times that some plant materials can curdle milk. Two have been used for centuries to make a distinctive group of cheeses. In Portugal and Spain, flowers of the wild cardoon thistles (*Cynara cardunculus* and *C. humilis*) have long been collected and dried in the summer, and then soaked in warm water in the winter to make sheep and goat cheeses (Portuguese Serra, Serpa, Azeitão; Spanish Serena, Torta del Casar, Pedroches). The cardoon rennets are unsuited to cow's milk, which they curdle but also turn bitter. Recent research has revealed that Iberian shepherds had indeed found a close biochemical relative of calf chymosin, which the thistle flower happens to concentrate in its stigmas.

The Propionibacteria An important bacterium in Swiss starter cultures is *Propionibacter shermanii,* the hole-maker. The propionibacteria consume the cheese's lactic acid during ripening, and convert it to a combination of propionic and acetic acids and carbon dioxide gas. The acids' aromatic sharpness, together with buttery diacetyl, contributes to the distinctive flavor of Emmental, and the carbon dioxide forms bubbles, or the characteristic "holes." The propionibacteria grow slowly, and the cheesemaker must coddle them along by ripening the cheese at an unusually high temperature—around 75ºF/24ºC—for several weeks. This need for warmth may reflect the cheese propionibacteria's original home, which was probably animal skin. (At least three other species of propionibacteria inhabit moist or oily areas of human skin, and *P. acnes* takes advantage of plugged oil glands.)

The Smear Bacteria The bacterium that gives Münster, Epoisses, Limburger, and other strong cheeses their pronounced stink, and contributes more subtly to the flavor of many other cheeses, is *Brevibacterium linens.* As a group, the brevibacteria appear to be natives of two salty environments: the seashore and human skin. Brevibacteria grow at salt concentrations that inhibit most other microbes, up to 15% (seawater is just 3%). Unlike the starter species, the brevibacteria don't tolerate acid and need oxygen, and grow only on the cheese surface, not inside. The cheesemaker encourages them by wiping the cheese periodically with brine, which causes a characteristic sticky, orange-red "smear" of brevibacteria to develop. (The color comes from a carotene-related pigment; exposure to light usually intensifies the color.) They contribute a more subtle complexity to cheeses that are wiped for only part of the ripening (Gruyère) or are ripened in humid conditions (Camembert). Smear cheeses are so reminiscent of cloistered human skin because both *B. linens* and its human cousin, *B. epidermidis,* are very active at breaking down protein

Why Some People Can't Stand Cheese

The flavor of cheese can provoke ecstasy in some people and disgust in others. The 17th century saw the publication of at least two learned European treatises "*de aversatione casei,*" or "on the aversion to cheese." And the author of "*Fromage*" in the 18th-century *Encyclopédie* noted that "cheese is one of those foods for which certain people have a natural repugnance, of which the cause is difficult to determine." Today the cause is clearer. The fermentation of milk, like that of grains or grapes, is essentially a process of limited, controlled spoilage. We allow certain microbes and their enzymes to decompose the original food, but not beyond the point of edibility. In cheese, animal fats and proteins are broken down into highly odorous molecules. Many of the same molecules are also produced during uncontrolled spoilage, as well as by microbial activity in the digestive tract and on moist, warm, sheltered areas of human skin.

An aversion to the odor of decay has the obvious biological value of steering us away from possible food poisoning, so it's no wonder that an animal food that gives off whiffs of shoes and soil and the stable takes some getting used to. Once acquired, however, the taste for partial spoilage can become a passion, an embrace of the earthy side of life that expresses itself best in paradoxes. The French call a particular plant fungus the *pourriture noble,* or "noble rot," for its influence on the character of certain wines, and the Surrealist poet Leon-Paul Fargue is said to have honored Camembert cheese with the title *les pieds de Dieu*—the feet of God.

into molecules with fishy, sweaty, and garlicky aromas (amines, isovaleric acid, sulfur compounds). These small molecules can diffuse into the cheese and affect both flavor and texture deep inside.

The Molds, Especially Penicillium Molds are microbes that require oxygen to grow, can tolerate drier conditions than bacteria, and produce powerful protein- and fat-digesting enzymes that improve the texture and flavor of certain cheeses. Molds readily develop on the rind of almost any cheese that is not regularly wiped to prevent it. The French St.-Nectaire develops a surface as variegated as lichen-covered rocks in the fields, with spots of bright yellow or orange standing out from a complex, muted background. Some cheeses are gardened to allow a diverse flora to develop, while others are seeded with one particular desired mold. The standard garden variety molds come from the large and various genus *Penicillium,* which also gave us the antibiotic penicillin.

Blue Molds *Penicillium roqueforti,* as its name suggests, is what gives sheep's milk Roquefort cheese its veins of blue. It and its cousin *P. glaucum* also color the interior of Stilton and Gorgonzola and the surface of many aged goat cheeses with the complex pigment produced in their fruiting structures. The blue penicillia are apparently unique in their ability to grow in the low-oxygen (5%, compared to 21% in the air) conditions in small fissures and cavities within cheese, a habitat that echoes the place that gave Roquefort its mold in the first place: the fissured limestone caves of the Larzac. The typical flavor of blue cheese comes from the mold's metabolism of milk fat, of which *P. roqueforti* breaks up 10 to 25%, liberating short-chain fatty acids that give the peppery feel to sheep's milk and goat milk blues, and breaking the longer chains and converting them into substances (methyl ketones and alcohols) that give the characteristic blue aroma.

White Molds In addition to the blue penicillia, there are the white ones, all strains of *P. camemberti,* which make the small, milder surface-ripened soft cow's milk cheeses of northern France, Camembert and Brie and Neufchâtel. The white penicillia create their effects mainly by protein breakdown, which contributes to the creamy texture and provides flavor notes of mushrooms, garlic, and ammonia.

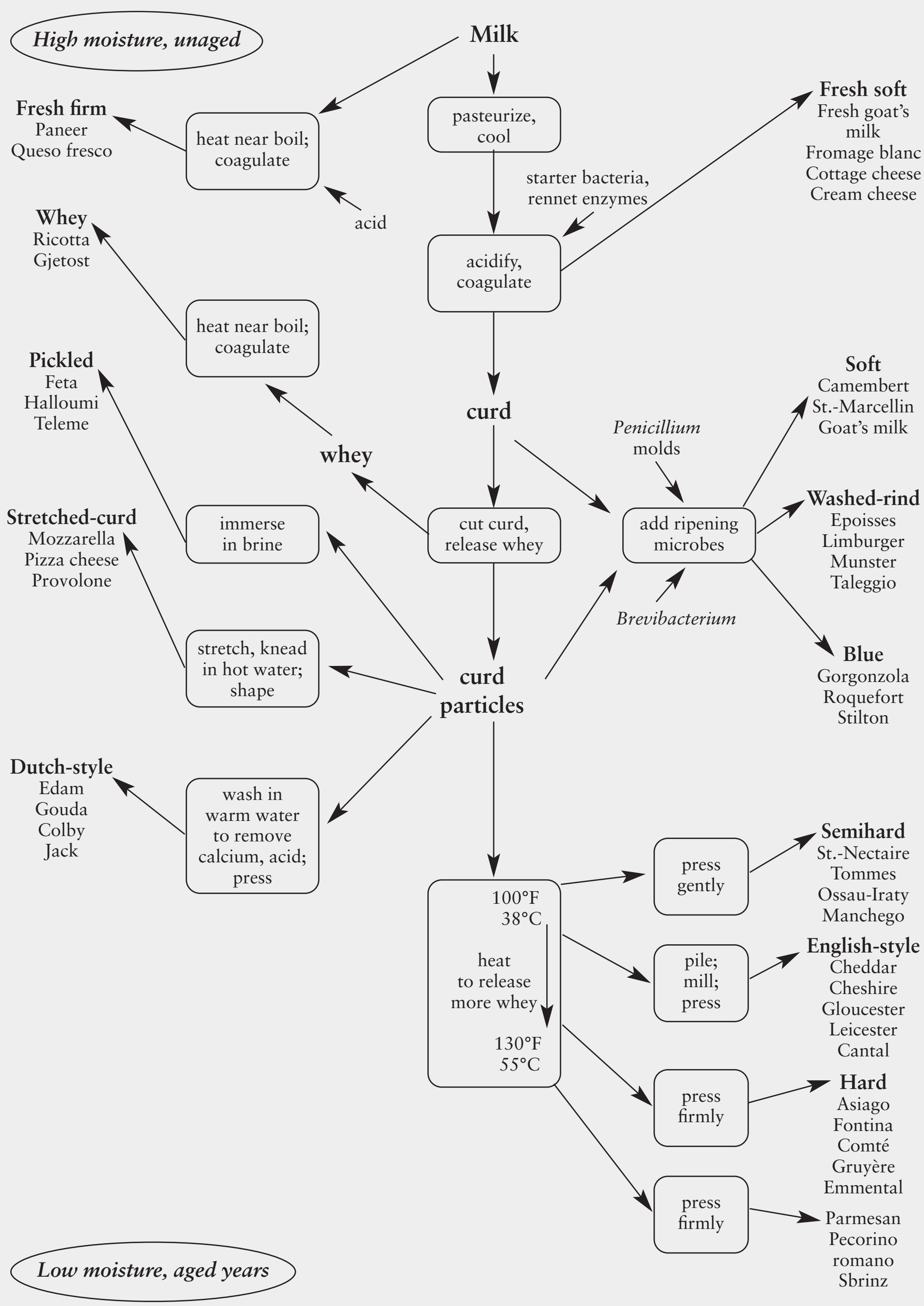
Making Cheese

There are three stages in the transformation of milk into cheese. In the first stage, lactic acid bacteria convert milk sugar into lactic acid. In the second stage, while the acidifying bacteria are still at work, the cheesemaker adds the rennet, curdles the casein proteins, and drains the watery whey from the concentrated curds. In the last stage, ripening, a host of enzymes work together to create the unique texture and flavor of each cheese. These are mainly protein- and fat-digesting enzymes, and they come from the milk, from bacteria originally present in the milk, the acidifying bacteria, the rennet, and any bacteria or molds enlisted especially for the ripening process.

Cheese is certainly an expression of the milk, enzymes, and microbes that are its major ingredients. But it is also—perhaps above all—an expression of the skill and care of the cheesemaker, who chooses the ingredients and orchestrates their many chemical and physical transformations. Here is a brief summary of the cheesemaker's work.

Curdling With the exception of some fresh cheeses, the cheesemaker curdles nearly all cheeses with a combination of starter-bacteria acid and rennet. Acid and rennet form very different kinds of curd structures—acid a fine, fragile gel, rennet a coarse but robust, rubbery one—so their relative contributions, and how quickly they act, help determine the ultimate texture of the cheese. In a predominantly acid coagulation, the curd forms over the course

How Some Familiar Cheeses Are Made



of many hours, is relatively soft and weak, and has to be handled gently, so it retains much of its moisture. This is how fresh cheeses and small, surface-ripened goat cheeses begin. In a predominantly rennet coagulation, the curd forms in less than an hour, is quite firm, and can be cut into pieces the size of a wheat grain to extract large amounts of whey. This is how large semihard and hard cheeses begin, from Cheddar and Gouda to Emmental and Parmesan. Cheeses of moderate size and moisture content are curdled with a moderate amount of rennet.

Draining, Shaping, and Salting the Curds The curds can be drained of their whey in several ways, depending on how much moisture the cheesemaker wants to remove from the curd. For some soft cheeses, the whole curd is carefully ladled into molds and allowed to drain by force of gravity alone, for many hours. For firmer cheeses, the curd is precut into pieces to provide more surface area from which the whey can drain or be actively pressed. The cut curd of large hard cheeses may also be "cooked" in its whey to 130ºF/55ºC, a temperature that not only expels whey from the curd particles, but also affects bacteria and enzymes, and encourages flavor-producing chemical reactions among some milk components. Once the curd pieces are placed in the mold that gives the cheese its final shape, they may be pressed to squeeze out yet more moisture.

The cheesemaker always adds salt to the new cheese, either by mixing dry salt with the curd pieces or by applying dry salt or brine to whole cheese. The salt provides more than its own taste. It inhibits the growth of spoilage microbes, and it's an essential regulator of cheese structure and the ripening process. It draws moisture out of the curds, firms the protein structure, slows the growth of ripening microbes, and alters the activity of ripening enzymes. Most cheeses contain between 1.5 and 2% salt by weight; Emmental is the least salty traditional cheese at about 0.7%, while feta, Roquefort, and pecorino may approach 5%.

Ripening, or *Affinage* Ripening is the stage during which microbes and milk enzymes transform the salty, rubbery, or crumbly curd into a delicious cheese. The French term for ripening, *affinage,* comes from the Latin *finus,* meaning "end" or "ultimate point," and was used in medieval alchemy to describe the refining of impure materials. For at least 200 years it has also meant bringing cheeses to the point at which flavor and texture are at their best. Cheeses have lives: they begin young and bland, they mature into fullness of character, and they eventually decay into harshness and coarseness. The life of a moist cheese like Camembert is meteoric, its prime come and gone in weeks, while the majority of cheeses peak at a few months, and a dry Comté or Parmesan slowly improves for a year or more.

The cheesemaker initiates and manages this maturation process by controlling the temperature and humidity at which the cheese is stored, conditions that determine the moisture content of the cheese, the growth of microbes, the activity of enzymes, and the development of flavor and texture. Specialist cheese merchants in France and elsewhere are also *affineurs*: they buy cheeses before they have fully matured, and carefully finish the process on their premises, so that they can sell the cheeses at their prime.

Industrial producers usually ripen their cheeses only partly, then refrigerate them to

OPPOSITE: *Principal cheese families. Only distinctive processing steps are shown; most cheeses are also salted, shaped in molds, and aged for some time. Curdling the milk, cutting the curd, heating the curd particles, and pressing are methods of removing progressively more moisture from a cheese, slowing its aging, and extending its edible lifetime.*

suspend their development before shipping. This practice maximizes the cheeses' stability and shelf life at the expense of quality.

The Sources of Cheese Diversity

So these are the ingredients that have generated the great diversity of our traditional cheeses: hundreds of plants, from scrubland herbs to alpine flowers; dozens of animal breeds that fed on those plants and transformed them into milk; protein-cutting enzymes from young animals and thistles; microbes recruited from meadow and cave, from the oceans, from animal insides and skins; and the careful observation, ingenuity, and good taste of generations of cheesemakers and cheese lovers. This remarkable heritage underlies even today's simplified industrial cheeses.

The usual way of organizing the diversity of cheeses into a comprehensible system is to group them by their moisture content and the microbes that ripen them. The more moisture removed from the curd, the harder the cheese's eventual texture, and the longer its lifespan. A fresh cheese with 80% water lasts a few days, while a soft cheese (45–55%) reaches its prime in a few weeks, a semihard cheese (40–45%) in a few months, a hard cheese (30–40%) after a year or more. And ripening microbes create distinctive flavors. The box on p. 60 shows how cheesemakers create such different cheeses from the same basic materials.

Choosing, Storing, and Serving Cheese

It has always been a challenge to choose a good cheese, as Charlemagne's instructor admitted (p. 53). A late medieval compendium of maxims and recipes for the

Cheese Flavors from Proteins and Fats

The flavor of a good cheese seems to fill the mouth, and that's because enzymes from the milk and rennet and microbes break down the concentrated protein and fat into a wide range of flavor compounds.

The long, chain-like casein proteins are first broken into medium-sized pieces called peptides, some still tasteless, some bitter. Usually these are eventually broken down by microbial enzymes into the 20 individual protein building blocks, the amino acids, a number of which are sweet or savory. The amino acids can in turn be broken into various amines, some of which are reminiscent of ocean fish (trimethylamine), others of spoiling meat (putrescine); into strong sulfur compounds (a specialty of smear bacteria), or into simple ammonia, a powerful aroma that in overripened cheeses is harsh, like household cleaner. Though few of these sound appetizing, bare hints of them together build the complexity and richness of cheese flavor.

Then there are the fats, which are broken down into fatty acids by blue-cheese *Penicillium roqueforti* and by special enzymes added to Pecorino and Provolone cheeses. Some fatty acids (short-chain) have a peppery effect on the tongue and an intensified sheepy or goaty aroma. The blue molds further transform some fatty acids into molecules (methyl ketones) that create the characteristic aroma of blue cheese. And the copper cauldrons in which the Swiss cheeses and Parmesan are made damage some milk fat directly, and the fatty acids thus liberated are further modified to create molecules with the exotic aromas of pineapple and coconut (esters, lactones).

The more diverse the cast of ripening enzymes, the more complex the resulting collection of protein and fat fragments, and the richer the flavor.

middle-class household, known as *Le Ménagier de Paris,* includes this formula "To recognize good cheese":

Not at all white like Helen,
Nor weeping, like Magdalene.
Not Argus, but completely blind,
And heavy, like a buffalo.
Let it rebel against the thumb,
And have an old moth-eaten coat.
Without eyes, without tears, not at all white,
Moth-eaten, rebellious, of good weight.

But these rules wouldn't work for young goat cheeses (white and coatless), Roquefort (with its pockets of whey), Emmental (eyefull and light), or Camembert (which should give when thumbed). As always, the proof is in the tasting.

These days, the most important thing is to understand that bulk supermarket cheeses are only pale (or dyed) imitations of their more flavorful, distinctive originals. The way to find good cheeses is to buy from a specialist who loves and knows them, chooses the best and takes good care of them, and offers samples for tasting.

Cut to Order Whenever possible, buy portions that are cut while you watch. Precut portions may be days or weeks old, and their large exposed surfaces inevitably develop rancid flavors from contact with air and plastic wrap. Exposure to light in the dairy case also damages lipids and causes off-flavors in as little as two days; in addition it bleaches the annatto in orange-dyed cheeses, turning it pink. Pregrated cheese has a tremendous surface area, and while it is often carefully wrapped, it loses much of its aroma and its carbon dioxide, which also contributes the impression of staleness.

Cool, Not Cold If cheese must be kept for more than a few days, it's usually easiest to refrigerate it. Unfortunately, the ideal conditions for holding cheese—a humid 55–60ºF/12–15ºC, simply a continuation of its ripening conditions—is warmer than most refrigerators, and cooler and moister than most rooms. Refrigeration essentially puts cheese into suspended animation, so if you want an immature soft cheese to ripen further, you'll need to keep it warmer.

Cheeses should never be served direct from the refrigerator. At such low temperatures the milk fat is congealed and as hard as refrigerated butter, the protein network unnaturally stiff, the flavor molecules imprisoned, and the cheese will seem rubbery and flavorless. Room temperature is best, unless it's so warm (above about 80ºF/26ºC) that the milk fat will melt and sweat out of the cheese.

Cheese Crystals

Cheeses usually have such a smooth, luscious texture, either from the beginning or as a hard cheese melts in the mouth, that an occasional crunch comes as a surprise. In fact a number of cheeses develop hard, salt-like crystals of various kinds. The white crystals often visible against the blue mold of a Roquefort, or detectable in the rind of a Camembert, are calcium phosphate, deposited because the *Penicillium* molds have made the cheese less acid and calcium salts less soluble. In aged Cheddar there are often crystals of calcium lactate, formed when ripening bacteria convert the usual form of lactic acid into its less soluble mirror ("D") image. In Parmesan, Gruyère, and aged Gouda, the crystals may be calcium lactate or else tyrosine, an amino acid produced by protein breakdown that has limited solubility in these low-moisture cheeses.

Loose Wrapping Tight wrapping in plastic film is inadvisable for three reasons: trapped moisture and restricted oxygen encourages the growth of bacteria and molds, not always the cheese's own; strong volatiles such as ammonia that would otherwise diffuse from the cheese instead impregnate it; and trace volatile compounds and plastic chemicals migrate into the cheese. Whole, still-developing cheeses should be stored unwrapped or very loosely wrapped, other cheeses loosely wrapped in wax paper. Stand them on a wire rack or turn them frequently to prevent the bottom from getting soggy. It can be fun to play the role of *affineur* and encourage surface or blue mold from a good Camembert or Roquefort to grow on a fresh goat cheese or in a piece of standard Cheddar. But there's some risk that other microbes will join in. If a piece of cheese develops an unusual surface mold or sliminess or an unusual odor, the safest thing is to discard it. Simply trimming the surface will not remove mold filaments, which can penetrate some distance and may carry toxins (p. 67).

Rinds Should cheese rinds be eaten? It depends on the cheese and the eater. The rinds of long-aged cheeses are generally tough and slightly rancid, and are best avoided. With softer cheeses it's largely a matter of taste. The rind can offer an interesting contrast to the interior in both flavor and texture. But if safety is a concern, then consider the rind a protective coating and trim it off.

COOKING WITH CHEESE

When used as an ingredient in cooking, cheese can add both flavor and texture: either unctuousness or crispness, depending on circumstances. In most cases, we want the cheese to melt and either mix evenly with other ingredients or spread over a surface. A certain giving cohesiveness is part of the pleasure of melted cheese. Stringy cheese can be enjoyable on pizzas, but a nuisance in more formal dishes. To understand cheese cooking, we need to understand the chemistry of melting.

Cheese Melting What is going on when we melt a piece of cheese? Essentially two things. First, at around 90ºF, the milk fat melts, which makes the cheese more supple, and often brings little beads of melted fat to the surface. Then at higher temperatures—around 130ºF/55ºC for soft cheeses, 150ºF/65ºC for Cheddar and Swiss types, 180ºF/82ºC for Parmesan and pecorino—enough of the bonds holding the casein proteins together are broken that the protein matrix collapses, and the piece sags and flows as a thick liquid. Melting behavior is largely determined by water content. Low-moisture hard cheeses require more heat to melt because their protein molecules are more concentrated and so more intimately bonded to each other; and when melted, they flow relatively little. Separate pieces of grated moist mozzarella will melt together, while flecks of Parmesan remain separate. With continued exposure to high heat, moisture will evaporate from the liquefied cheese, which gets progressively stiffer and eventually resolidifies. Most cheeses will leak some melted fat, and extensive breakdown of the protein fabric accentuates this in high-fat cheeses. The ratio of fat to surrounding protein is just 0.7 in part-skim Parmesan, around 1 in mozzarella and the alpine cheeses, but 1.3 in Roquefort and Cheddar, which are especially prone to exuding fat when melted.

Nonmelting Cheeses There are several kinds of cheese that do not melt on heating: they simply get drier and stiffer. These include Indian paneer and Latin queso blanco, Italian ricotta, and most fresh goat cheeses; all of them are curdled exclusively or primarily by means of acid, not rennet. Rennet creates a malleable structure of large casein micelles held together by relatively few calcium atoms and hydrophobic bonds, so this structure is readily weakened by heat. Acid, on the other hand, dissolves the calcium glue that holds the casein proteins together in micelles (p. 20), and it eliminates each protein's negative electrical charge, which would otherwise cause the proteins to repel each other. The proteins are free to flock together and bond extensively into microscopic clumps. So when an acid curd is heated, the first thing to be shaken loose is not the proteins, but water: the water boils away, and this simply dries out and concentrates the protein even further. This is why firm paneer and queso blanco can be simmered or fried like meat, and goat cheeses and ricotta maintain their shape on pizzas or in pasta stuffings.

Stringiness Melted cheese becomes stringy when mostly intact casein molecules are cross-linked together by calcium into long, rope-like fibers that can stretch but get stuck to each other. If the casein has been attacked extensively by ripening enzymes, then the pieces are too small to form fibers; so well-aged grating cheeses don't get stringy. The degree of cross-linking also matters: a lot and the casein molecules are so tightly bound to each other that they can't give with pulling, and simply snap apart; a little and they pull apart right away. The cross-linking is determined by how the cheese was made: high acidity removes calcium from the curd, and high moisture, high fat, and high salt help separate casein molecules from each other. So the stringiest cheeses are moderate in acidity, moisture, salt, and age. The most common stringy cheeses are intentionally fibrous mozzarella, elastic Emmental, and Cheddar. Crumbly cheeses like Cheshire and Leicester, and moist ones like Caerphilly, Colby, and Jack are preferred for making such melted preparations as Welsh rarebit, stewed cheese, and grilled-cheese sandwiches. Similarly, Emmental's alpine cousin Gruyère is preferred in fondues because it's moister, fatter, and saltier. And the Italian grating cheeses—Parmesan, grana Padano, the pecorinos—have had their protein fabric sufficiently broken that its pieces readily disperse in sauces, soups, risottos, polenta, and pasta dishes.

Cheeses are at their stringiest right around their melting point—which usually means right about the point that a piping-hot dish gets cool enough to eat—and get more so the more they are stirred and stretched. One French country dish, *aligot* from the Auvergne, calls for unripened Cantal cheese to be sliced, mixed with just-boiled potatoes, and sweepingly stirred until it forms an elastic cord that can stretch for 6 to 10 feet/2–3 meters!

Cheese Sauces and Soups When cheese is used to bring flavor and richness to a sauce (Gruyère or Parmesan in French *sauce Mornay,* Fontina in Italian *fonduta*) or a soup, the aim is to integrate the cheese evenly into the liquid. There are several ways to avoid the stringiness, lumps, and fat separation that result when the cheese proteins are allowed to coagulate.

- Avoid using a cheese that is prone to stringiness in the first place. Moist or well-aged grating cheeses blend better.
- Grate the cheese finely so that you can disperse it evenly throughout the dish from the beginning.
- Heat the dish as little as possible after the cheese has been added. Simmer the other ingredients together first, let the pot cool a bit, and *then* add the cheese. Remember that temperatures above the cheese's melting point will tend to tighten the protein patches into hard clumps and squeeze out their fat. On the other hand, don't let the dish cool down too much before serving. Cheese gets stringier and tougher as it cools down and congeals.
- Minimize stirring, which can push the dispersed patches of cheese protein back together into a big sticky mass.
- Include starchy ingredients that will coat the protein patches and fat pockets and keep them apart. These stabilizing ingredients include flour, cornstarch, and arrowroot.

- If the flavor of the dish permits, include some wine or lemon juice—a preventive or emergency measure well known to fans of the ultimate cheese sauce, *fondue*.

Cheese Fondue In the Swiss Alps, where for centuries cheese has been melted in a communal pot at the table and kept hot over a flame for dipping bread, it's well known that wine can help keep melted cheese from getting stringy or seizing up. The ingredients in a classic fondue, in fact, are just alpine cheese—usually Gruyère—a *tart* white wine, some kirsch, and sometimes (for added insurance) starch. The combination of cheese and wine is delicious but also savvy. The wine contributes two essential ingredients for a smooth sauce: water, which keeps the casein proteins moist and dilute, and tartaric acid, which pulls the cross-linking calcium off of the casein proteins and binds tightly to it, leaving them glueless and happily separate. (Alcohol has nothing to do with fondue stability.) The citric acid in lemon juice will do the same thing. If it's not too far gone, you can sometimes rescue a tightening cheese sauce with a squeeze of lemon juice or a splash of white wine.

Toppings, Gratins When a thin layer of cheese is heated in the oven or under a broiler—on a gratin, a pizza, or bruschetta—the intense heat can quickly dehydrate the casein fabric, toughen it, and cause its fat to separate. To avoid this, watch the dish carefully and remove it as soon as the cheese melts. On the other hand, browned, crisp cheese is quite delicious: the *religieuse* at the bottom of the fondue pot crowns the meal. If you want a cheese topping to brown, then pick a robust cheese that resists fat loss and stringiness. The grating cheeses are especially versatile; Parmesan can be formed into a thin disk and melted and lightly browned in a frying pan or the oven, then molded into cups or other shapes.

Process and Low-Fat Cheeses

Process cheese is an industrial version of cheese that makes use of surplus, scrap, and unripened materials. It began as a kind of resolidified, long-keeping fondue made from trimmings of genuine cheeses that were unsaleable due to partial defects or damage. The first industrial attempts to melt together a blend of shredded cheeses were made at the end of the 19th century. The key insight—the necessity of "melting salts" analogous to the tartaric acid and citric acid in a fondue's wine or lemon juice—came in Switzerland in 1912. Five years later, the American company Kraft patented a combination of citric acid and phosphates, and a decade after that it brought out the popular cheddar look-alike Velveeta.

Today, manufacturers use a mixture of sodium citrate, sodium phosphates, and sodium polyphosphates, and a blend of new, partly ripened, and fully ripened cheeses. The polyphosphates (negatively charged chains of phosphorus and oxygen atoms that attract a cloud of water molecules) not only remove calcium from the casein matrix, but also bind to the casein themselves, bringing moisture with them and thus further loosening the protein matrix. The same salts that melt the component cheeses into a homogeneous mass also help the resulting blended cheese melt nicely when cooked. This characteristic, together with its low cost, has made process cheese a popular ingredient in fast-food sandwiches.

Low- and no-fat "cheese products" replace fat with various carbohydrates or proteins. When heated, such products don't melt; they soften and then dry out.

Cheese and Health

Cheese and the Heart As a food that is essentially a concentrated version of milk, cheese shares many of milk's nutritional advantages and disadvantages. It's a rich source of protein, calcium, and energy. Its abundant fat is highly saturated and therefore tends to raise blood cholesterol levels. However, France and Greece lead the world in per capita cheese consumption, at better than 2 oz/60 gm per day, about double the U.S. figures, yet they're remarkable among Western countries for their relatively low rates of heart disease, probably thanks to their high consumption of heart-protective vegetables, fruits, and wine (p. 253). Eating cheese as part of a balanced diet is fully compatible with good health.

Food Poisoning

Cheeses Made from Raw and Pasteurized Milks Government concerns about the danger of the various pathogens that can grow in milk led to the U.S. requirement (originating in 1944, reaffirmed in 1949, and extended to imports in 1951) that all cheeses aged less than 60 days be made with pasteurized milk. Since 1948 there have been only a handful of outbreaks of food poisoning in the United States caused by cheese, nearly all involving contamination of the milk or cheese after pasteurization. In Europe, where young raw-milk cheeses are still legal in some countries, most outbreaks have also been caused by pasteurized cheeses. Cheeses in general present a relatively low risk of food poisoning. Because any soft cheese contains enough moisture to permit the survival of various human pathogens, both pasteurized and unpasteurized versions are probably best avoided by people who may be especially vulnerable to infection (pregnant women, the elderly and chronically ill). Hard cheeses are inhospitable to disease microbes and very seldom cause food poisoning.

Storage Molds In addition to the usual disease microbes, the molds that can grow on cheese are of some concern. When cheeses are held in storage for some time, toxin-producing foreign molds (*Aspergillus versicolor, Penicillium viridicatum* and *P. cyclopium*) may occasionally develop on their rinds and contaminate them to the depth of up to an inch/2 cm. This problem appears to be very rare, but does make it advisable to discard cheeses overgrown with unusual mold.

Amines There is one normal microbial product that can cause discomfort to some people. In a strongly ripened cheese, the casein proteins are broken down to amino acids, and the amino acids can be broken down into amines, small molecules that can serve as chemical signals in the human body. Histamine and tyramine are found in large quantities in Cheddar, blue, Swiss, and Dutch-style cheeses, and can cause a rise in blood pressure, headaches, and rashes in people who are especially sensitive to them.

Tooth Decay Finally, it has been recognized for decades that eating cheese slows tooth decay, which is caused by acid secretion from relatives of a yogurt bacterium (especially *Streptococcus mutans*) that adhere to the teeth. Just why is still not entirely clear, but it appears that eaten at the end of a meal, when streptococcal acid production is on the rise, calcium and phosphate from the cheese diffuse into the bacterial colonies and blunt the acid rise.

CHAPTER 2

EGGS

The egg is one of the kitchen's marvels, and one of nature's. Its simple, placid shape houses an everyday miracle: the transformation of a bland bag of nutrients into a living, breathing, vigorous creature. The egg has loomed large as a symbol for the enigmatic origins of animals, of humans, of gods, of the earth, of the entire cosmos. The Egyptian Book of the Dead, the Indian Rg Veda, Greek Orphic mysteries, and creation myths throughout the world have been inspired by the eruption of life from within a lifeless, blank shell.

Humpty Dumpty has had a great fall! If eggs inspire any notable feeling today, it's boredom tinged by wariness. The chicken egg is now an industrial product, so familiar that it would be almost invisible—except that it was stigmatized by the cholesterol phobia of the 1970s and 1980s.

Neither familiarity nor fear should obscure eggs' great versatility. Their contents are primal, the unstructured stuff of life. This is why they are protean, why the cook can use them to generate such a variety of structures, from a light, insubstantial meringue to a dense, lingeringly rich custard. Eggs reconcile oil and water in a host of smooth sauces; they refine the texture of candies and ice creams; they give flavor, substance, and nutritiousness to soups, drinks, breads, pastas, and cakes; they put a shine on pastries; they clarify meat stocks and wines. On their own, they're amenable to being boiled, fried, deep-fried, baked, roasted, pickled, and fermented.

Meanwhile modern science has only deepened the egg's aptness as an emblem of creation. The yolk is a stockpile of fuel obtained by the hen from seeds and leaves, which are in turn stockpiles of the sun's radiant energy. The yellow pigments that gave the yolk its name also come directly from plants, where they protect the chemical machinery of photosynthesis from being overwhelmed by the sun. So the egg does embody the chain of creation, from the developing chick back through the hen to the plants that fed her, and then to the ultimate source of life's fire, the yellow sphere of the sky. An egg is the sun's light refracted into life.

Many animals lay eggs, and humans exploit a number of them, from pigeons and turkeys to wild birds, penguins, turtles, and crocodiles. The chicken egg is by far the most commonly eaten in most countries, so I'll concentrate on it, with occasional asides on duck eggs.

THE CHICKEN AND THE EGG

Over the centuries there have been several clever answers to the conundrum, Which came first: the chicken or the egg? The Church Fathers sided with the chicken, pointing out that according to Genesis, God first created the creatures, not their reproductive apparatus. The Victorian Samuel Butler awarded the egg overall priority when he said that a chicken is just an egg's way of making another egg. About one point, however, there is no dispute: eggs existed long before chickens did. Ultimately, we owe our soufflés and sunny-sides-up to the invention of sex.

The Evolution of the Egg

Sharing DNA Defined broadly, the egg is a kind of cell that is specialized for the process of sexual reproduction, in which two parents contribute genes to the making of a new individual. The first living things were single cells and reproduced on their own, each cell simply making a copy of its DNA and then dividing itself into two cells.

> The World Egg
>
> In the beginning this world was nonexistent. It became existent. It developed. It turned into an egg. It lay for the period of a year. It split apart. One of the parts became silver, one gold.
>
> That which was silver is this earth. That which was gold is the sky. That which was the outer membrane is the mountains. That which was the inner membrane is clouds and mist. What were the veins are the rivers. What was the fluid within is the ocean.
>
> What was born from the egg is the sun. When it was born, shouts and hurrahs and all beings and all desires rose up toward it. Therefore at its rise and at its every return, shouts and hurrahs and all beings and all desires rise up toward it.
>
> —*Chandogya Upanishad*, ca. 800 BCE

The first sexual organisms, probably single-celled algae, paired up and exchanged DNA with each other before dividing—a mixing that greatly facilitated genetic change. Specialized egg and sperm cells became necessary around a billion years ago, when many-celled organisms evolved and this simple transfer of DNA was no longer possible.

What makes an egg an egg? Of the two reproductive cells, it's the larger, less mobile one. It receives the sperm cell, accommodates the joining of the two gene sets, and then divides and differentiates into the embryonic organism. It also provides food for at least the initial stages of this growth. This is why eggs are so nutritious: Like milk and like plant seeds, they are actually designed to be foods, to support new creatures until they are able to fend for themselves.

Improving the Package The first animal eggs were released into the equable oceans, where their outer membrane could be simple and their food supply minimal. Some 300 million years ago, the earliest fully land-dwelling animals, the reptiles, developed a self-contained egg with a leathery skin that slowed fatal water loss, and with enough food to support prolonged embryonic development into a fully formed animal. The eggs of birds, animals that arose some 100 million years later, are a refined version of the primitive reptile egg. Their hard, mineralized shell is impermeable enough that the embryo can develop in the driest habitats; and they contain an array of antimicrobial defenses. These developments made the bird egg into an ideal human food. It contains a sizeable and balanced portion of animal nutrients; and it's so well packaged that it keeps for weeks with little or no care.

The Chicken, from Jungle to Barnyard

Eggs, then, are nearly a billion years older than the oldest birds. The genus *Gallus,* to which the chicken belongs, is a mere 8 million years old, and *Gallus gallus,* the chicken species, has been around only for the last 3 to 4 million years.

For a barnyard commoner, the chicken has a surprisingly exotic background. Its immediate ancestors were jungle fowl native to tropical and subtropical Southeast Asia and India. The chicken more or less as we know it was probably domesticated in Southeast Asia before 7500 BCE, which is when larger-than-wild bones date from in Chinese finds far north of the jungle fowl's current range. By 1500 BCE chickens had found their way to Sumer and Egypt, and they arrived around 800 BCE in Greece, where they became known as "Persian birds," and where quail were the primary source of eggs.

The Domestic Egg We'll never know exactly why chickens were domesticated, but they may well have been valued more for their prolific egg production than for their meat. Some birds will lay only a set number of eggs at a time, no matter what happens to the eggs. Others, including the

Food Words: *Egg* and *Yolk*

Egg comes from an Indo-European root meaning "bird."

The brusque-sounding *yolk* is rich in overtones of light and life. It comes from the Old English for "yellow," whose Greek cousin meant "yellow-green," the color of new plant growth. Both the Old English and the Greek derive ultimately from an Indo-European root meaning "to gleam, to glimmer." The same root gave us *glow* and *gold.*

chicken, will lay until they accumulate a certain number in the nest. If an egg is taken by a predator, the hen will lay another to replace it—and may do so indefinitely. Over a lifetime, these "indeterminate layers" will produce many more eggs than the "determinate" layers. Wild Indian jungle fowl lay clutches of about twelve glossy, brown eggs a few times each year. In industrial production—the ecological equivalent of unlimited food resources combined with unrelenting predation—their domesticated cousins will lay an egg a day for a year or more.

Cooked Eggs Doubtless bird eggs have been roasted ever since humans mastered fire; in *As You Like It* Shakespeare has Touchstone call Corin "damned, like an ill-roasted egg, all on one side." Salting and pickling eggs are ancient treatments that preserved the spring's bounty for use throughout the year. We know from the recipes of Apicius that the Romans ate *ova frixa, elixa, et hapala*—fried, boiled, and "soft" eggs—and the *patina,* which could be a savory quiche or a sweet custard. By medieval times, the French were sophisticated omelet makers and the English were dressing poached eggs with the sauce that would come to be called *crème anglaise.* Savory yolk-based sauces and egg-white foams developed over the next three centuries. By around 1900, Escoffier had a repertoire of more than 300 egg dishes, and in his *Gastronomie Pratique,* Ali Bab gave a playful recipe for a "Symphony of Eggs"—a four-egg omelet containing two chopped hard-cooked and six whole poached eggs.

The Industrial Egg

Hen Fever The chicken underwent more evolutionary change between 1850 and 1900 than it had in its entire lifetime as a species, and under an unusual selection pressure: the fascination of Europeans and Americans with the exotic East. A political opening between England and China brought specimens of previously unknown Chinese breeds, the large, showy Cochins, to the West. These spectacular birds, so different from the run of the barnyard, touched off a chicken-breeding craze comparable to the Dutch tulip mania of the 17th century. During this "hen fever," as one observer of the American scene called

Roman Custards, Savory and Sweet

Patina of Soles

Beat and clean the soles and put in patina [a shallow pan]. Throw in oil, liquamen [fish sauce], wine. While the dish cooks, pound and rub pepper, lovage, oregano; pour in some of the cooking liquid, add raw eggs, and make into one mass. Pour over the soles and cook on a slow fire. When the dish has come together, sprinkle with pepper and serve.

"Cheese" Patina

Measure out enough milk for your pan, mix with honey as for other milk dishes, add five eggs for [a pint], three for [a half-pint]. Mix them in the milk until they make one mass, strain into a dish from Cuma, and cook over a slow fire. When it is ready, sprinkle with pepper and serve.

—from Apicius, first few centuries CE

it, poultry shows were very popular and hundreds of new breeds were developed.

Ordinary farm stock was also improved. Just a few decades after its arrival in the United States from Tuscany around 1830, descendents of the White Leghorn emerged as the champion layers. Versions of the Cornish, itself the offshoot of Asiatic fighting breeds, were deemed the best meat birds; and the Plymouth Rock and Rhode Island Red, whose eggs are brown, were bred as dual-purpose chickens. As interest in the show birds faded, the egg and meat breeds became ever more dominant. Today, an egg or meat chicken is usually the product of four purebred grandparents. Nearly all of the diversity generated in the 1800s has disappeared. Among industrialized countries, only France and Australia have remained independent of the handful of multinational corporations that provide laying stock to the egg industry.

Mass Production The 20th century saw the general farm lose its poultry shed to the poultry farm or ranch, which has in turn been split up into separate hatcheries and meat and egg factories. Economies of scale dictate that production units be as large as possible—one caretaker can manage a flock of 100,000, and many ranches now have a million or more laying hens. Today's typical layer is born in an incubator, eats a diet that originates largely in the laboratory, lives and lays on wire and under lights for about a year, and produces between 250 and 290 eggs. As Page Smith and Charles Daniel put it in their *Chicken Book,* the chicken is no longer "a lively creature but merely an element in an industrial process whose product [is] the egg."

A Medieval Omelet and English Cream

Arboulastre *(An Omelet)*

[First prepare mixed herbs, including rue, tansy, mint, sage, marjoram, fennel, parsley, violet leaves, spinach, lettuce, clary, ginger.] Then have seven eggs well beaten together, yolks and whites, and mix with the herbs. Then divide in two and make two *allumelles,* which are fried in the following manner. First you heat your frying pan well with oil, butter, or whatever fat you like. When it is well heated, especially toward the handle, mix and cast your eggs upon the pan, and turn frequently with a paddle over and under; then throw some good grated cheese on top. Know that it is done thus because if you mix the cheese with the eggs and herbs, when you fry the *allumelle,* the cheese that is underneath sticks to the pan. . . . And when your herbs are fried in the pan, shape your *arboulastre* into a square or round form, and eat it neither too hot nor too cold.

—*Le Ménagier de Paris*, ca. 1390

Poche to Potage (Poached Eggs in Crème Anglaise)

Take eggs and break them into boiling water, and let them seethe, and when they are done take them out, and take milk and yolks of eggs, and beat them well together, and put them in a pot; and add sugar or honey, and color it with saffron, and let it seethe; and at the first boil take it off, and cast therein powder of ginger, and dress the cooked eggs in dishes, and pour the pottage above, and serve it forth.

—from a manuscript published in *Antiquitates Culinariae,* 1791 (ca. 1400)

Benefits and Costs The industrialization of the chicken has brought benefits, and these shouldn't be underestimated. A pound of broiler can now be produced from less than two pounds of feed, a pound of eggs from less than three, so both chickens and eggs are bargains among animal foods. Egg quality has also improved. City and country dwellers alike enjoy fresher, more uniform eggs than formerly, when small-farm hens ran free and laid in odd places, and when spring eggs were stored until winter in limewater or waterglass (see p. 115). Refrigeration alone has made a tremendous difference. Year-round laying (made possible by controlled lighting and temperature), prompt gathering and cooling, and daily shipping by rapid, refrigerated transport mean that good eggs deteriorate much less between hen and cook than they did in the more relaxed, more humane past.

There are drawbacks to the industrial egg. While average quality has improved, people who pay close attention to eggs say that flavor has suffered: that the chicken's natural, varied diet of grains, leaves, and bugs provides a richness that the commercial soy and fish meals don't. (This difference has proven hard to document in taste tests; see p. 87.) In addition, mass husbandry has played a role in the rising incidence of salmonella contamination. "Spent" hens are often recycled into feed for the next generation of layers, so that salmonella infection is readily spread by careless processing. Finally, there is a more difficult question: whether we can enjoy good, cheap eggs more humanely, without reducing descendents of the spirited jungle fowl to biological machines that never see the sun, scratch in the dust, or have more than an inch or two to move.

Freer Range? Enough people have become uncomfortable with the excesses of industrialization, and willing to pay a substantial premium for their eggs, that smaller-scale, "free-range" and "organically fed" laying flocks have made a comeback in the United States and Europe. Swiss law now requires that all hens in that country have free access to the outdoors. The term "free-range" can be misleading; it sometimes means only that the chickens live in a slightly larger cage than usual, or have brief access to the outdoors. Still, with people eating fewer eggs in the home, spending so little on those eggs, and paying more attention to what they eat, the odds are good that this modest de-industrialization of the egg will continue.

EGG BIOLOGY AND CHEMISTRY

How the Hen Makes an Egg

The egg is so familiar that we seldom remember to marvel at its making. All animals work hard at the business of reproduction, but the hen does more than most. Her "reproductive effort," defined as the fraction of body weight that an animal deposits daily in her potential offspring, is 100 times greater than a human's. Each egg is about 3% of the hen's weight, so in a year of laying, she converts about eight times her body weight into eggs. A quarter of her daily energy expenditure goes toward egg-making; a duck puts in half.

The chicken egg begins with the pinhead-sized white disc that we see riding atop the yellow yolk. This is the business end of the egg, the living germ cell that contains the hen's chromosomes. A hen is born with several thousand microscopic germ cells in her single ovary.

Making the Yolk As the hen grows, her germ cells gradually reach a few millimeters in diameter, and after two or three months accumulate a white, primordial form of yolk inside their thin surrounding membrane. (The white yolk can be seen in a hard-cooked egg; see box, p. 74.) When the hen reaches laying age at between four and six months, the egg cells begin to mature, with different cells at different stages at any given time. Full maturation takes about ten weeks. During the tenth, the germ cell rapidly accumulates yellow yolk, mostly fats and proteins, which is synthesized in the hen's liver. Its color depends on the pigments in the hen's feed; a diet rich in corn or alfalfa makes a deeper yellow. If the hen feeds only once or twice a day, her yolk will show distinct layers of dark and light. In the end, the yolk comes to dwarf the germ cell, containing as it must the provisions for 21 days during which the chick will develop on its own.

Making the White The rest of the egg provides both nourishment and protective housing for the germ cell. Its construction takes about 25 hours and begins when the ovary releases the completed yolk. The yolk is then gripped by the funnel-shaped opening of the oviduct, a tube 2–3 feet/0.6–0.9 meter long. If the hen has mated in recent days, there will be sperm stored in a "nest" at the upper end of the oviduct, and one will fuse with the egg cell. Fertilized or not—and most eggs are not—the yolk spends two to three hours slowly passing down the upper end of the oviduct. Protein-secreting cells in the oviduct lining add a thickening layer to its membrane, and then coat it with about half the final volume of the egg white, or *albumen* (from the Latin *albus,* meaning "white"). They apply this portion of albumen in four layers that are alternately thick and thin in consistency.

The first thick layer of albumen protein is twisted by spiraling grooves in the oviduct wall to form the *chalazae* (from the Greek for "small lump," "hailstone"), two dense, slightly elastic cords which anchor the yolk to the ends of the shell and allow it to rotate while suspending it in the middle of the egg. This system keeps as much cushioning albumen as possible between the embryo and the shell, and prevents premature contact between shell and embryo, which could distort the embryo's development.

Membranes, Water, and Shell Once the albumen proteins have been applied to the yolk, it spends an hour in the next section of the oviduct being loosely enclosed in two tough, antimicrobial protein membranes that are attached to each other everywhere except for one end, where the air pocket will later develop to supply the hatching chick with its first gulps of air. Then comes a long stretch—19 or 20 hours—in the 2-inch-/5-cm-long uterus, or shell gland. For five hours, cells in the uterus wall pump water and salts through the membranes and into the albumen and "plump" the egg to its full volume. When the membranes are taut, the uterine lining secretes calcium carbonate and protein to form the shell, a process that takes about 14 hours. Since the embryo needs air, the shell is riddled (especially at the blunt end) with some 10,000 pores that add up to a hole about 2 mm in diameter.

Germ-Side Up: Primordial Yolk

Have you ever noticed that when you crack open a raw egg, the germ cell—the pinhead-sized white disc that carries the hen's DNA—usually comes to the top of the yolk? It does so because the channel of primordial white yolk below it is less dense than the yellow yolk—so the egg cell's side of the yolk is lighter, and rises. In the intact egg, the chalazae allow the germ cell to return to the top whenever the hen rearranges her eggs.

That persistent bit of uncoagulated yolk at the center of a hard-cooked egg is primordial white yolk, especially rich in iron, which the hen deposits in its eggs when they're barely a quarter-inch/6 mm in diameter.

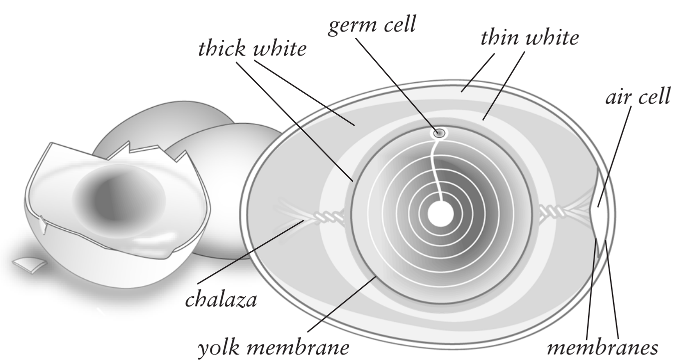
Cuticle and Color The hen's finishing touch on her egg is a thin proteinaceous cuticle. This coating initially plugs up the pores to slow water loss and block the entry of bacteria, but gradually fractures to allow the chick to get enough oxygen. Along with the cuticle comes color, in the form of chemical relatives of hemoglobin. Egg color is determined by the hen's genetic background, and has no relation to the egg's taste or nutritional value. Leghorns lay very lightly pigmented "white" eggs. Brown eggs are produced by breeds that were originally dual-purpose egg and meat birds, including Rhode Island Reds and Plymouth Rocks; New Hampshire and Australorps hens were bred for intensive brown-egg production. Chinese Cochin hens paint their eggs with fine yellow dots. Thanks to a dominant trait unknown in any other wild or domestic chickens, the rare Chilean Araucana lays blue eggs. Crosses between Araucanas and brown-egg breeds make both blue and brown pigments and thus green shells.

The completed egg is expelled blunt end first about 25 hours after leaving the ovary. As the egg cools down from the hen's high body temperature (106ºF/41ºC), its contents shrink slightly. This contraction pulls the inner shell membrane away from its outer partner at the blunt end and thereby forms the air space, whose size is an indicator of egg freshness (p. 81).

The Yolk

The yolk accounts for just over a third of a shelled egg's weight, and its biological purpose is almost exclusively nutritive. It carries three-quarters of the calories and most of the iron, thiamin, and vitamin A of the egg as a whole. The yolk's yellow color comes not from the vitamin-A precursor beta-carotene, the orange pigment in carrots and other plant foods, but from plant pigments called xanthophylls (p. 267), which the hen obtains mainly from alfalfa and corn feeds. Producers may supplement the feeds with marigold petals and other additives to deepen the color. Duck yolks owe their deeper orange color both to beta-carotene and to the reddish pigment canthaxanthin, which wild ducks obtain from small water insects and crustaceans, egg-laying ducks from feed supplements. One minor component of the yolk that can cause a major culinary disaster is the starch-digesting enzyme amylase, which has liquefied many a normal-looking pie filling from within (see p. 98).

Spheres Within Spheres That's a yolk by numbers and nutrients. But there's a lot more to this concentrated pool of the sun's rays. Its structure is intricate, much like a Chinese set of nested spheres carved from a single block of jade. We see the first layer of structure whenever we cut into a hard-cooked egg. Where heat gels the white into



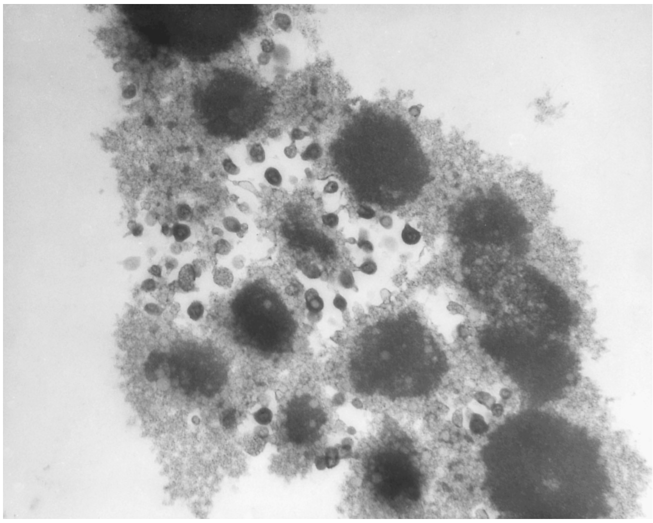
The structure of the hen's egg. The egg white provides physical and chemical protection for the living germ cell, and protein and water for its development into a chick. The yolk is rich in fats, proteins, vitamins and minerals. The layering of color in the yolk is caused by the hen's periodic ingestion of grain and its fat-soluble pigments.

a smooth, continuous mass, the yolk sets into a crumbly mass of separate particles. The intact yolk turns out to consist of spherical compartments about a tenth of a millimeter across, each contained within a flexible membrane, and so tightly packed that they're distorted into flat-sided shapes (much like the oil droplets that egg yolk stabilizes in mayonnaise; see p. 626). When a yolk is cooked intact, these spheres harden into individual particles and give the yolk its characteristic crumbly texture. But break the yolk out before you cook it so that the spheres can move freely, and it becomes less granular.

What's inside these large yolk spheres? Though we think of the yolk as rich and fatty, in fact its chambers are filled mostly with water. Floating in that water are subspheres about one hundredth the size of the spheres. The subspheres are too small to see with the naked eye or to be broken up by a kitchen beating. But they can be seen indirectly, and disrupted chemically. Yolk is cloudy because these subspheres are large enough to deflect light and prevent it from passing through the yolk directly. Add a pinch of salt to a yolk (as you do when making mayonnaise) and you'll see the yolk become simultaneously clearer and thicker. Salt breaks apart the light-deflecting subspheres into components that are too small to deflect light—and so the yolk clears up.

And what do the subspheres contain? A mixture similar to the liquid that surrounds them in the spheres. First, water. Dissolved in the water, proteins: hen blood proteins outside the subspheres; inside, phosphorus-rich proteins that bind up most of the egg's iron supply. And suspended in the water, *sub*subspheres about 40 times smaller than the subspheres, some of which turn out to be familiar from the human body. The subsubspheres are aggregates of four different kinds of molecules: a core of fat surrounded by a protective shell of protein, cholesterol, and phospholipid, a hybrid fat-water mediator which in the egg is mainly lecithin. Most of these subsubspheres are "low-density lipoproteins," or LDLs—essentially the same particles that we keep track of in our own blood to monitor our cholesterol levels.

Stand back from all these spheres within spheres and the picture becomes less dizzying. The yolk is a bag of water that contains free-floating proteins and protein-fat-cholesterol-lecithin aggregates—and these



An egg yolk granule as seen through the electron microscope. It has fallen apart after immersion in a salt solution, and is an intricate assembly of proteins, fats, phospholipids, and cholesterol.

lipoprotein aggregates are what give the yolk its remarkable capacities for emulsifying and enriching.

The White

Next to the yolk's riches, the white seems colorless and bland. It accounts for nearly two thirds of the egg's shelled weight, but nearly 90% of that is water. The rest is protein, with only traces of minerals, fatty material, vitamins (riboflavin gives the raw white a slightly yellow-green cast) and glucose. The quarter-gram of glucose, which is essential for the embryo's early growth, isn't enough to sweeten the white, though in such preparations as long-cooked eggs (p. 89) and thousand-year preserved eggs (p. 116) it's sufficient to turn the white a dramatic brown. The white's structural interest is limited to the fact that it comes in two consistencies, thick and thin, with the yolk cords being a twisted version of the thick.

Protective Proteins Pale though it is, the egg white has surprising depths. Of course it supplies the developing embryo with essential water and protein. But biochemical studies have revealed that the albumen proteins are not mere baby food. At least four of the proteins block the action of digestive enzymes. At least three bind tightly to vitamins, which prevents them from being useful to other creatures, and one does the same for iron, an essential mineral for bacteria and animals alike. One protein inhibits the reproduction of viruses, and another digests the cell walls of bacteria. In sum, the egg white is first of all a chemical shield against infection and pre-

The Proteins in Egg White

Protein	Percent of Total Albumen Protein	Natural Functions	Culinary Properties
Ovalbumin	54	Nourishment; blocks digestive enzymes?	Sets when heated to 180ºF/80ºC
Ovotransferrin	12	Binds iron	Sets when heated to 140ºF/60ºC or foamed
Ovomucoid	11	Blocks digestive enzymes	?
Globulins	8	Plug defects in membranes, shell?	Foam readily
Lysozyme	3.5	Enzyme that digests bacterial cell walls	Sets when heated to 170ºF/75ºC; stabilizes foam
Ovomucin	1.5	Thickens albumen; inhibits viruses	Stabilizes foam
Avidin	0.06	Binds vitamin (biotin)	?
Others	10	Bind vitamins (2+); block digestive enzymes (3+) . . .	?