One of life's simple pleasures is really quite complicated

THE COMPLEXITY OF COFFEE

By Ernesto Illy

Photographs by Tina West

For sheer sensory enjoyment, few everyday experiences can compete with a good cup of coffee. The alluring aroma of steaming hot coffee just brewed from freshly roasted beans can drag sleepers from bed and pedestrians into cafés. And many millions worldwide would find getting through the day difficult without the jolt of mental clarity imparted by the caffeine in coffee. But underlying this seemingly commonplace beverage is a profound chemical complexity. Without a deep understanding of how the vagaries of bean production, roasting and preparation minutely affect the hundreds of compounds that define coffee's flavor, aroma and body, a quality cup would be an infrequent and random occurrence.

Connoisseurs agree that the quintessential expression of coffee is espresso: that diminutive heavy china cup half-filled with a dark, opaque brew topped by a velvety thick, reddish-brown froth called *crema*. Composed of tiny gas bubbles encased in thin films, the surprisingly persistent *crema* locks in the coffee's distinctive flavors and aromas and much of its heat as well. Espresso—the word refers to a serving made on request expressly for the occasion—is brewed by rapidly percolating a small quantity of pressurized, heated water through a compressed cake of finely ground roasted coffee. The resulting concentrated liquor contains not only soluble solids but also a diverse array of aromatic substances in a dispersed emulsion of tiny oil droplets, which together give espresso its uniquely rich taste, smell and "mouthfeel."

Aficionados consider perfectly brewed espresso to be the ultimate in coffee because its special preparation amplifies and exhibits the inherent characteristics of the beans. Espresso is useful for our purposes as it is in effect a distillation of all the numerous techniques by which coffee can be made, including the Turkish method and various infusion and filter drip processes [*see box on page 91 for descriptions of alternative coffee-preparation methods*]. To know espresso is to know coffee in all its forms.

High-quality coffee arises from maintaining close control over a multitude of factors in the field, in the plant and in the cup. Coffee cultivation entails myriad variables that must be monitored and regulated. Once a coffee bean is grown, nothing can be added or removed: the quality must already be present. For a single portion of espresso, 50 to 55 roasted coffee beans are required; a single imperfect bean will taint the whole sufficiently to be noticeable. This is because human olfaction and taste senses originated as defense mechanisms that protected our ancestors from rotten—hence, unhealthy—foods. Only through modern technology can one economically and consistently identify 50 nearly perfect beans.

Growing Coffee

RAW COFFEE BEANS are the seeds of plants belonging to the Rubiaceae family, which comprises at least 66 species of the genus *Coffea*. The two species that are commercially exploited are *Coffea arabica,* which accounts for two thirds of world production, and *C. canephora,* often called robusta coffee, with one third of global output. Robusta coffee plants and all wild coffee species have 22 chromosomes, whereas arabica has 44. Therefore, arabica and other coffee species cannot be crossed to produce a hybrid plant.

Robusta is a high-yielding and disease-resistant tree standing up to 12 meters tall that grows best in warm, humid climes. It produces a cup featuring substantial body, a relatively harsh, earthy aroma, and an elevated caffeine content that ranges from 2.4 to 2.8 percent by weight. Although robusta is sold by many purveyors, it does not give rise to the highest-quality coffee.

Arabica, which originated in the Ethiopian highlands, is a medium- to low-yielding, rather delicate tree from five to six meters tall that requires a temperate climate and considerable growing care. Commercially grown coffee bushes are pruned to a height of 1.5 to 2.0 meters. Coffee made from arabica beans has an intense, intricate aroma that can be reminiscent of flowers, fruit, honey, chocolate, caramel or toasted bread. Its caffeine content never exceeds 1.5 percent by weight. Because of its superior quality and taste, arabica sells for a higher price than its hardy, rougher cousin.

A good rainfall induces arabica coffee plants to blossom, and some 210 days afterward red or yellow fruit called cherries appear. Each cherry contains two oblong seeds—the coffee beans. Because both flower and fruit can be present simultaneously on the same branch, the picker's forefinger and thumb are the best tools to gather just the ripe cherries. Stripping entire branches by hand or using automated harvesting machines does not discriminate between the ripe and the unripe cherries.

The ultimate quality of the resulting coffee beans depends on the genetics of the plant, the soil in which it grows and the microclimate, which encompasses factors such as altitude, the amount of rainfall and sunlight, and daily temperature fluctuations. Along with the roasting processes that are applied, these agricultural and geographical considerations are responsible for the taste differences among the many varieties of coffee beans that suppliers combine to produce the various distinctive blends one can purchase.

Processing Coffee

COFFEE CHERRIES must be processed immediately after harvest to prevent spoilage. Producers employ two processing methods: sun-drying and washing. Effective sun-drying is accomplished by spreading the cherries out on a patio and stirring the desiccating fruit frequently to evenly heat and aerate it. The dried cherries are run through a machine that crushes the hulls and then removes both the hulls and the surrounding parchment membrane layer, thus freeing the beans for sorting and bagging. In the alternative approach, the fruit is mechanically pulped, washed, and finally dried and liberated from the parchment covering. The goal of either route is the same: the 65 percent water content of the coffee cherry is reduced to the 10 to 12 percent moisture level of a prime raw, or green, coffee bean.

One of the greatest challenges in producing superior coffee is ensuring that one starts with exceptional green beans. Premium producers, such as illycaffè, based in Trieste, Italy, use many sophisticated process-control techniques to minimize the percentage of defective coffee beans, including ultraviolet fluorescence analysis to spot moldy beans and trichromatic mapping to generate a color fingerprint (yellow-green, red and infrared) of each lot of beans. At illycaffè, a dichromatic sorting system developed in collaboration with the English company Sortex is applied as a final control right before roasting. As beans fall into bins, photoelectric cells detect duds, signaling for them to be rejected individually with a puff from an air nozzle. The sorting operation is accomplished at a speed that no human hand can match (400 beans a second) and with a precision that even the most highly trained eye is incapable of.

A perfect mature green coffee bean is composed of cells with uncommonly thick walls: as much as five to seven microns, an exception in the vegetal kingdom. During roasting, these 30- to 40-micron-diameter cells serve as tiny reactors in which all the key heat-driven chemical reactions occur that generate coffee's seductive taste and fragrance. The cells of immature beans feature thinner walls. Unripe beans also lack the important aromatic precursor proteins that develop in the last stages of the ripening process.

THE AUTHOR

ERNESTO ILLY is chairman of illycaffè, a family business based in Trieste, Italy, that his father founded in 1933. Over two million illy espressos are served every day in Italy alone. Illy holds a doctorate in chemistry and has completed advanced studies in molecular biology. His goal is to harness science to create the truly perfect cup of espresso.

Fermented beans are composed of cells that have been emptied of these crucial constituents by molds or bacteria.

Roasting Coffee

ROASTING is a pyrolytic (heat-driven) process that greatly increases the chemical complexity of coffee. The aroma of green coffee contains some 250 different volatile molecular species, whereas roasted coffee gives rise to more than 800.

When subjected to the staged heating of a roasting machine (basically, a huge, hot rotating cylinder), residual water inside each cell is converted to steam, which promotes diverse, complicated chemical reactions among the cornucopia of sugars, proteins, lipids and minerals within [*see box on next page*]. At high heat, from 185 to 240 degrees Celsius, sugars combine with amino acids, peptides and proteins according to a well-known caramelization process called Maillard's reaction. The end products are brownish, bittersweet glycosylamine and melanoidins—which give rise to coffee's dominant taste—along with carbon dioxide (up to 12 liters per kilogram of roasted coffee).

Simultaneously, a wide variety of lower-mass aromatic molecules emerge; these volatile compounds give coffee its familiar fragrance. Pressure inside each cell increases to as much as 20 to 25 atmospheres as the steam and carbon dioxide try to escape but are sealed in by the thick, low-porosity cell walls and a coating of oil. Some cells eventually burst, creating the characteristic popping sound of roasting coffee. During roasting, coffee bean volume increases by half or more; bean mass decreases by a fifth.

Depending on the temperatures and procedures applied, the roasting process can last from 90 seconds to as long as 40 minutes. Twelve minutes, however, is the traditional duration. The thermodynamics of the intracellular reactions differ according to roasting time, and so does the final result. A short roasting time, which requires a great deal of thermal energy, minimizes weight loss but imparts to the cup a metallic bitterness stemming from the presence of polyphenols that do not have enough time to react properly. Long roasting periods, frequently used in poorer countries in which many consumers can afford only low-priced, defective beans, forces all the off-flavors and fragrances to leave the beans. Sadly, the desirable tastes and aromas flee as well, yielding a rather bitter cup.

The higher the final temperature of the roasting, the less desirable the aroma will be and the stronger the bitterness. Conversely, low roasting temperatures fail to develop fully the welcome aromas, and acidity tends to come to the fore.

Smelling Coffee

AROMA SCIENCE is highly complex. Researchers typically analyze the fragrances evolved during coffee bean roasting by gas chromatography coupled with olfactometry, in which skilled testers sniff and define the smell of each recognizable element. Mass spectrometry is frequently then applied to identify the chemical composition of each odor. Sniffing roasted coffee aromas that have been fractionated by a gas chromatograph is an enlightening experience: one may recognize the aromas of roses, Darjeeling tea, chocolate, vanilla and violets, as well as truffles, soup, cheese, sweat and even what is called cat scent, which, if diluted, smells like sauvignon blanc wine but in a concentrated sample is disgusting.

In the laboratories of illycaffè, technicians focus on the strongest odorants. Imagine listening to a recording of a choir of 800 singers that includes the strong solo voices of Jessye Norman, Luciano Pavarotti and several other virtuosi who tend to dominate the ensemble. If the volume of the playback is reduced, the stronger voices will still be recognizable even as the choir's sound fades away. Diluting the aroma of coffee is analogous; beyond a certain point, only the strongest compounds are perceived. Unfortunately, the most powerful molecules in the smell of a coffee sample are those originating from defective beans.

Molecules such as ethylbutanoate and ethylglycolate, which are responsible for the unpleasant aroma of immature beans, ruin a cup of coffee by their very presence. Likewise, methylisoborneol and trichloroanisole (TCA) molecules produce the characteristic earthy, chemical smell of ro-

With more than 400 BILLION CUPS consumed every year, coffee is the world's most popular beverage (besides water, of course).

Coffee ranks SECOND ONLY TO PETROLEUM in terms of dollars traded worldwide (about $10.4 billion in exports in 2000).

ACCORDING TO A SURVEY OF 3,000 AMERICANS CONDUCTED BY THE NATIONAL COFFEE ASSOCIATION IN 2001:

Fifty-two percent of adults (older than 18 years) in the U.S. drink coffee every day, representing 107 MILLION daily drinkers. Another 28 percent of adults (57 MILLION) drink coffee occasionally.

American coffee drinkers consume, on average, 3.3 (NINE-OUNCE) CUPS OF COFFEE a day.

Controversy continues over whether SHADE-GROWN coffee should be promoted to enhance bird habitats.

Coffee and caffeine have been the subject of extensive scientific study during the past quarter of a century, with 1,500 TO 2,000 PAPERS PUBLISHED EVERY YEAR on the topic. Despite this close scrutiny, few negative health effects have been definitively linked to the moderate consumption (TWO CUPS A DAY) of caffeinated coffee. In fact, recent work indicates that roasted coffee can be a good source of antioxidants.

1000 B.C. TO A.D. 500 *The nomadic Oromos tribe, living in the kingdom of Kefa (in modern-day Ethiopia), eat coffee, crushed, mixed with fat and shaped into golf ball–size portions, as a pick-me-up.*

CIRCA 600 *Coffee is brought by traders across the Red Sea into Arabia (modern-day Yemen).*

LATE 1400s TO EARLY 1500s *Coffee beans, heretofore an Arabian monopoly, are brought to Turkey, Egypt and Syria by Muslim pilgrims returning from Mecca. Arabian-influenced coffeehouses open in Constantinople, Damascus and other Near Eastern cities, where European traders, particularly Venetians, are introduced to the beverage.*

CIRCA 1600 *Calling it "the bitter invention of Satan," advisers urge Pope Clement VIII to reject the favorite drink of the infidel Ottoman Turks. Instead he decides to give papal authority to coffee, making it acceptable for Roman Catholics.*

1616 *Dutch entrepreneurs start to cultivate coffee commercially, beginning with a coffee plant obtained from Yemen. By 1658 (according to some sources, the 1690s), the Dutch are growing coffee in Ceylon and their East Indian colony of Java.*

1714 *The mayor of Amsterdam presents the French king, Louis XIV, with a coffee plant from Java.*

1723 *Gabriel Mathieu de Clieu, a French naval officer, carries three coffee seedlings obtained under questionable circumstances from the Royal Botanical Gardens on a perilous voyage to the Caribbean island of Martinique, where one of the plants thrives.*

1727 *After having been called to arbitrate a border dispute between two coffee-growing colonies, Dutch Guiana and French Guiana, Francisco de Melo Palheta, a Portuguese Brazilian official, smuggles several coffee seedlings to his home estates.*

1903 *German coffee importer Ludwig Roselius perfects decaffeinated coffee.*

1933 *Francesco Illy patents the first automatic espresso machine.*

1961 *Ernesto Valente of Faema, an Italian coffee machine maker, designs the archetype of the modern espresso machine.*

busta coffees. TCA, which is also called Rio taste because it was first discovered in coffees grown around Rio de Janeiro, can be found in corked wines as well. Its perception threshold to the human olfactory system is shockingly low—six millionths of a billionth of a gram per milliliter.

Preparing Coffee

THE NEXT MAJOR STEP in the transformation of roasted beans into a cup of espresso is the extraction of the active components in the roasted and ground coffee by heated water. The interaction of hot water and coffee grounds is, however, subtly different when making common drip coffee than when making espresso.

When filter drip coffee is prepared, hot water passes through a loose aggregation of medium-size coffee grounds. During the four to six minutes of contact with the boiling water, most of the soluble substances present in the roasted coffee pass into solution. Thus, large quantities of highly soluble acids and caffeine dissolve into the cup. In contrast, the much shorter percolation time of espresso allows less acid and only 60 to 70 percent of the caffeine to dissolve into the brew.

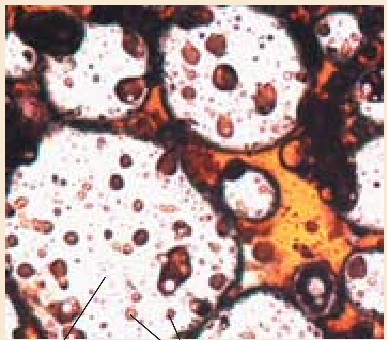
Brewing espresso requires specialized equipment that can heat water to a temperature of between 92 and 94 degrees C and pressurize it to nine atmospheres. Coffee, ground to a fine to medium consistency, is placed in a perforated basket and firmly tamped down to create a compacted bed of particles. The compressed grounds adhere to one another thanks to a thin coating of oil, which is as viscous as honey. The oil binds the particles together into a condensed maze of minuscule air passages. Experimentation has shown that the hydraulic resistance of this bed of coffee grounds must be slightly less than the pressure of the steaming-hot extraction water, allowing it to flow through at a rate of around a milliliter a second.

Using the recommended 30 seconds of percolation, a skilled *barista* (coffee bar technician) produces about 30 milliliters of dense coffee liquor covered by the all-important *crema*. If the color of the foam topping is light, it means that the espresso has been underextracted, probably because the grind was too coarse, the water temperature too low or the time too short. If the *crema* is very dark in hue and has a "hole" in the middle, it is likely that the consistency of the coffee grounds was too fine or the quantity of grounds was too large. An overextracted espresso exhibits either a white froth with large bubbles if the water was too hot or just a white spot in the center of the cup if the brewing time was too long.

The percolation process also washes out components present on the surface of the coffee grounds, including aroma-filled oil and bits of the cellular structure. The high pressure generated by the espresso

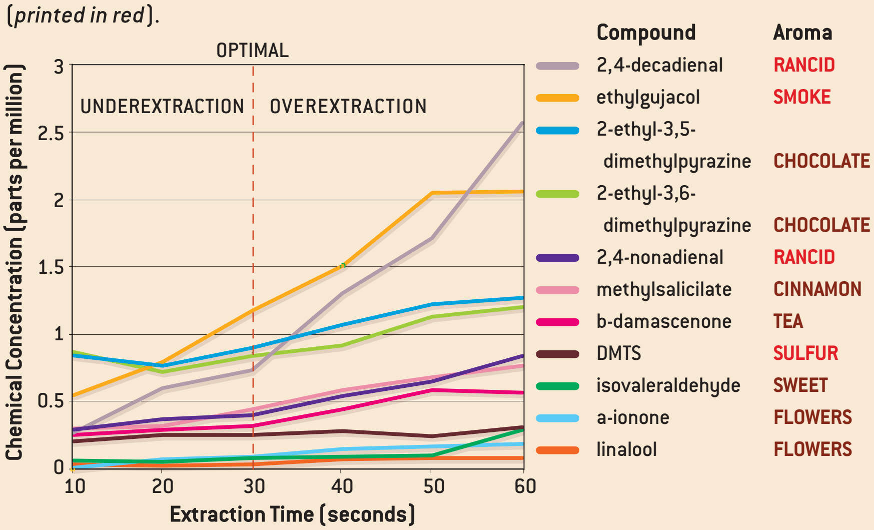
THE CHEMISTRY OF COFFEE

CREMA, the dense, reddish-brown foam that tops an espresso, is shown in an enlarged cross section. Composed mainly of tiny carbon dioxide and water vapor bubbles (*large circles*) surrounded by surfactant films, the *crema* also includes emulsified oils containing key aromatic compounds (*particles with red borders*) and dark fragments of the coffee bean cell structure.

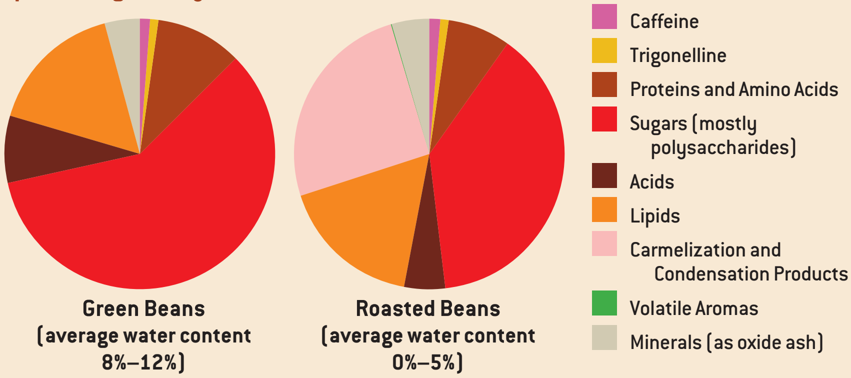


Cumulative Chemical Composition of Espresso with Increasing Extraction Time

THE OVEREXTRACTION of espresso (beyond the recommended 30 seconds) leads to the incorporation of undesirable and less soluble aromatic compounds into the drink (*printed in red*).



Chemical Composition of Raw and Roasted Arabica Coffee (percentage of dry matter)



ILLYCAFFÉ (*micrograph*); NINA FINKEL (*illustrations*)

OTHER COFFEE-BREWING TECHNIQUES

FILTER DRIP METHODS (automatic drip, Melitta, Chemex pots). These popular techniques employ finely ground coffee in receptacles lined with filter paper. A medium grind should be used with a reusable gold filter. There are two keys to making superior coffee using these processes: first, rinse the paper filter with boiling water to remove the papery smell; second, ensure that the near-boiling-hot brewing water takes no more than four to six minutes to pass through the grounds, thereby producing optimal extraction levels. The brewing time of an automatic drip machine can be controlled by tailoring the quantity of water so that it flows for the recommended four to six minutes.

French press or plunger pot. This apparatus steeps the coffee in the hot water before the grounds are filtered out. Combine heated water and coarsely ground coffee in the pot and allow it to infuse from two to five minutes, depending on the desired strength. Then press the wire-mesh filter/plunger slowly through the infusion, segregating the grounds at the bottom of the pot.

Turkish method. Unlike other brewing processes, gentle boiling of the coffee is desirable when using this method. Mix equal amounts of pulverized coffee, water and sugar in a special pot called an *ibrik,* which sits directly over the heat. Stir the mixture as it comes to a slow boil. Stop stirring when the powdered coffee no longer sticks to a spoon. As the brew just begins to boil and foam up, remove the *ibrik* from the heat. Tap the *ibrik* to reduce the foam somewhat. Repeat the process at least two additional times. The result is a uniquely thick, sweet brew.

Adapted from The Great Coffee Book, *by Timothy J. Castle and Joan Nielsen (Ten Speed Press, Berkeley, Calif., 1999).*

machine emulsifies a small amount of the oils, about 0.1 gram a cup. Intact cells in the grounds create a fine effervescence, which is derived from gases (especially carbon dioxide) passing through tiny pores in the cell walls. Some very fine grounds can also find their way into the beverage, along with cell wall fragments, which endow the foamy *crema* with what is called the tiger-skin look.

The final result is a polyphasic colloidal system, in which water molecules are bound to the dispersed gas bubbles, oil droplets and solid fragments, all of which are less than five microns in size. The colloidal character of the dispersion gives the drink high body, high viscosity and low surface tension. Espresso thus visibly coats our tongues and continues to release the aromatic volatiles dissolved in the emulsified oils as long as it remains there. These oily flavor/fragrance carriers mean that the great taste and aroma of a good espresso can be savored for as long as 20 minutes after it has been drunk. Luckily, the drinker need not know anything about the complex chemistry of coffee to enjoy it. SA

MORE TO EXPLORE

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International Coffee Organization: **www.ico.org**

International Scientific Association of Coffee: **www.asic-cafe.org**

Coffee industry–supplied information on coffee, caffeine and health: **www.coffeescience.org**