CHAPTER 1

BREWING QUALITY OVERVIEW

We wrote this book to help you better understand, appreciate, and apply the science behind the materials and processes of making **beer**. The better your grasp of **brewing** science, the more dependably you will be able to make delicious beer, and the more reliably you will be able to devise new beers to meet changing consumer preferences. So what is beer? How does beer differ from its **fermented beverage** brethren? The US legal definition is given in Section 19.3: “Flavored Malt Beverages”; a commercial definition encompasses the wide variety of products that are included in beer marketing, but in a book on brewing science, we will use a scientific definition. Beer is an **alcoholic beverage** derived from a source of **starch** without concentrating the alcohol content. “Derived from” covers a complex series of interacting steps, each of which influences the character of the final product and is ultimately the focus of this book. Brewing beer differs from **fermentation** of **wine** in that for brewing, a source of starch must first be converted into fermentable **sugars**. The brewer is responsible for management and control of all steps of the brewing process to produce a beer of reliable and reproducible quality.

There are four main ingredients in beer: water, **malt**, **hops**, and **yeast**. If randomly combined, these four ingredients might turn into an alcoholic beverage of questionable quality, but in this chemical process, the brewer is like a **catalyst**, a substance that guides and speeds up a **reaction**. Mastering

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the science of raw materials and the process steps of beer production is essential to making quality beer. We will start with a broad overview of the brewing process followed by a scientific history of beer and the scientific method. In learning how to conduct an experiment, you will begin to understand the process of troubleshooting problems in the **brewery**. Finally, as our major goal is to brew beer of excellent quality and consistency, we will discuss beer quality as defined in several contexts. Each of these topics will be discussed further in depth in the chapters that follow.

1.1 INGREDIENTS

In addition to the main ingredients, beer may be brewed with **adjuncts** and **processing aids.** Adjuncts are sources of starch or **sugar** other than malt. Processing aids are materials used to help give the beer desirable characteristics. Some common processing aids are **filtration media**, **finings**, carbon dioxide, **foam** enhancers, and coloring materials. In this overview, we will touch upon the main four ingredients. Adjuncts and processing aids are covered in later chapters.

Water

Beer is usually more than 90% water. Beer production can take as much as 12 volumes of water to make 1 volume of beer. Some breweries have been able to cut this ratio to three or less. Less water means less **energy** use, less wastewater for disposal, and less negative impact on the environment. Pure water is a characterless **compound** of fixed composition. It is supplied to breweries as a **mixture** with many **components** present in trace amounts. The nature and **concentrations** of these trace components are important to the character and quality of the beer. Water is usually modified to adjust the trace components. Water that is to be made into beer is sometimes called **brewing liquor**. Chapter 4 discusses brewing water in detail.

Malt

Brewing beer requires starch, which is usually derived from **cereal grain**. Malt is prepared from seeds of cereal grain by **steeping** (soaking in water), **germinating**, and drying. The malting process produces **enzymes** that convert starch to fermentable sugars. The most common grain for malting is **barley** (***Hordeum vulgare***), but wheat, rye, and oats can also be malted. Rice and **maize** (corn) can also be used as sources of starch for brewing but require special treatment. Since medieval times, malting has been a separate craft from brewing, requiring specialized facilities. Nonetheless, brewers need a basic understanding of the malting process to fully understand and apply malt as a raw material. Malt and malting will be discussed in Chapter 5.

Hops

The **hop** (***Humulus lupulus***) is a climbing plant, more specifically a **bine**. The fruits of the hop plant, hops, are boiled with the beer **wort** to provide bitterness and other flavors. Hops may also be added to the fermenter in a process called **dry hopping**. Hop compounds provide an antibacterial effect to help preserve the beer. There are many varieties of hops with different flavor profiles, as well as advanced hop products that can be easier to use than natural hops. Chapter 6 provides details about hops and their processing.

Yeast

Yeast is a single-cell **fungus** that converts sugar to **ethanol** and carbon dioxide. The action of yeast on sugar is fermentation. Most beer fermentation is carried out by one of two species of yeast: ***Saccharomyces pastorianus***, used for **lager beer**, and ***Saccharomyces cerevisiae***, used for **ale**. Some specialty beer styles are fermented with ***Brettanomyces*** *bruxellensis*, *Brettanomyces lambicus*, or related species. Within a particular yeast species, there are many variations, called **strains**. The species and strain of yeast affects the flavor and character of the beer. Yeast may be cultivated at the brewery or **pitched** directly from wet or dry commercial products. Processes and practices involving yeast are covered in detail in Chapters 10 and 11.

1.2 BREWING OVERVIEW

A graphical overview of the brewing process is provided in Figure 1.1. In brief:

- Malt and other grains are crushed in the **mill**. Crushed grain is called **grist**.
- The grist is loaded into the grist case until mashing.
- The grist is mixed with hot water in the **premasher** on its way into the **mash tun**.
- In the mash tun, enzymes from the malt cause the starch in the grist to be converted to soluble **extract**, which contains sugars that the yeast can ferment.
- The solution of extract, called wort, is separated from the remaining grist particles in the **lauter** tun. Extract that sticks to the particles is washed out with hot water in a process called **sparging**.

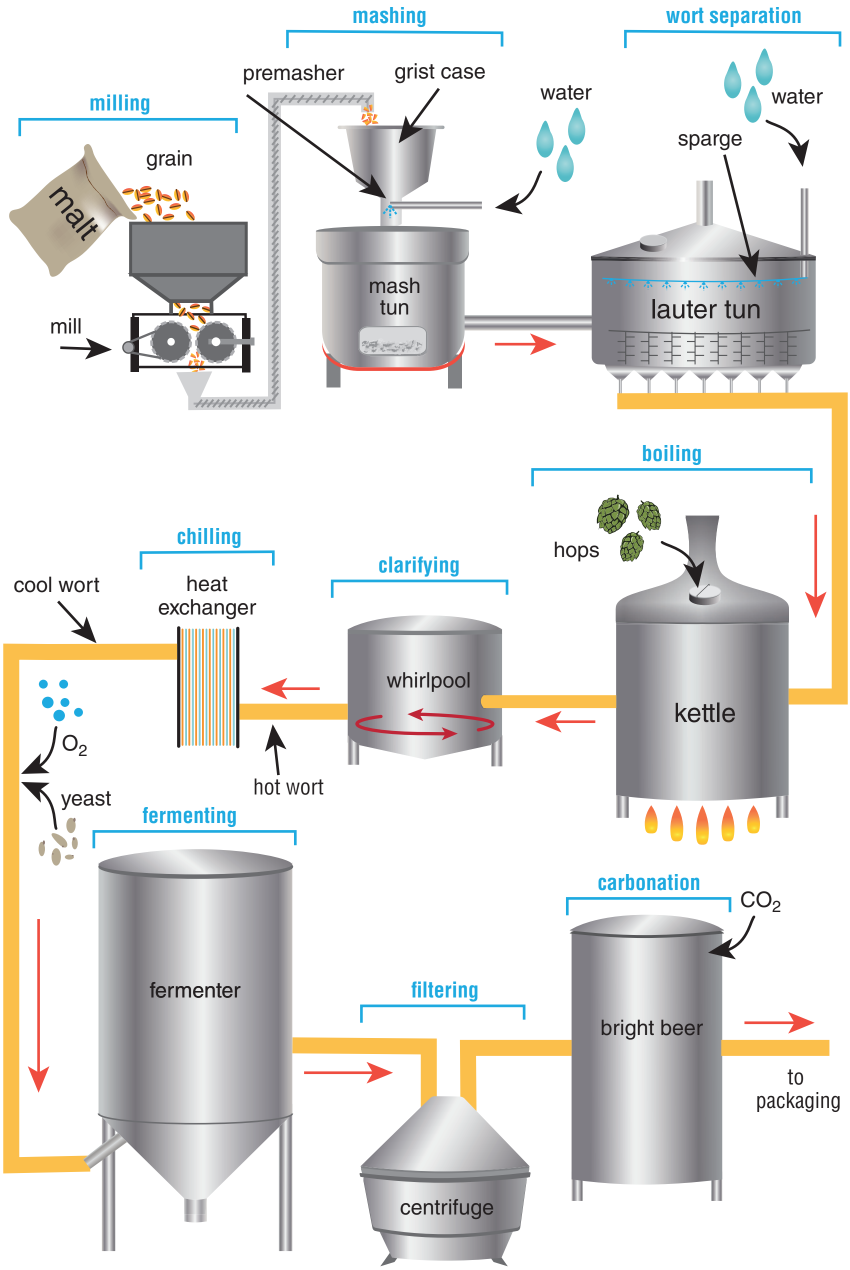

Figure 1.1 Overview of the brewing process in a four-vessel brewhouse.
Source: Drawing: Marcy Barth.

- The clear wort is boiled in the **kettle**. Hops are added.
- The remains of the hops and solids that form during boiling (**hot break** or **trub**) are removed in the whirlpool.
- The clear, boiling-hot wort is cooled in a **heat exchanger** called the wort chiller.
- During **knockout**, oxygen and yeast are added to the cool wort while it is pumped into a fermenter.
- After several days to more than a month of fermentation and **conditioning**, the yeast is removed from the beer, and the beer is pumped into the **bright beer tank**. Separation of yeast and solids may be facilitated by special equipment such as a **centrifuge** or **filter**. Carbon dioxide is added under pressure to provide the characteristic lively mouthfeel.
- The beer is served directly from the tank or packaged into secondary containers.

A summary of the duration and temperature ranges for each step in the brewing process is provided in Table 1.1. This table represents a general summary and overview; different breweries using different equipment and brewing different styles of beer may have quite different programs.

Milling

Malt is delivered to breweries in bulk (loose in a truck or rail car), in **super sacks**, or in bags. Malt must be milled, that is, crushed into small pieces to expose the starch, before it is used for brewing. Crushed grain is called grist. The device that performs the operation is a mill (Figure 1.2). The primary purpose of milling is to allow starch from the grain, enzymes from malt, and water to come into contact during the mashing step. A seed of grain is protected by a water-resistant **seed coat**, and a woody shell

TABLE 1.1 Brewing Steps, Durations, and Temperatures

Process Step	Duration	Temperature	
Milling	1–2 hours	Ambient	
Mashing	1–2 hours	45–67 °C	(113–153 °F)
Lautering/sparging	1–2 hours	75–78 °C	(167–172 °F)
Boiling	1–2 hours	105 °C	(221 °F)
Whirlpool	15–30 minutes	74–76 °C	(165–169 °F)
Fermentation (ale)	4–10 days	15–25 °C	(59–77 °F)
Conditioning (ale)	at least 1 day	−1 to 6 °C	(30–43 °F)
Filtration	2–12 hours	2–6 °C	(36–43 °F)
Packaging	<12 hours	2–6 °C	(36–43 °F)
Duration of typical shelf life	~6 months	Ambient	

Figure 1.2 Mill at Susquehanna Brewing Company. *Source*: Photo by Naomi Hampson.

called the **hull**. Milling splits the hull, breaks open the seed coat, and crushes the interior of the seed, producing additional **surfaces** where water can react with starch. Milling details affect the character of the beer and the efficiency of the process. It is preferred that the malt hulls be split but not pulverized because they will be needed to aid wort separation later in the process.

Mashing

During the mashing step, starch, which brewing yeast cannot ferment, is converted to smaller sugars that yeast can ferment. During mashing, hot water, sometimes called brewing liquor, is mixed with the grist to give a temperature in the range of 60–70 °C (140–158 °F). Sometimes, mashing starts at a lower temperature, and the temperature is raised continuously or in steps to influence the protein or **carbohydrate** profile. Mashing is conducted in a **mash conversion vessel** (**MCV**), also called a mash tun (Figure 1.3). The MCV may contain an agitation paddle for gentle mixing. The details of the time–temperature profile, the activities of enzymes

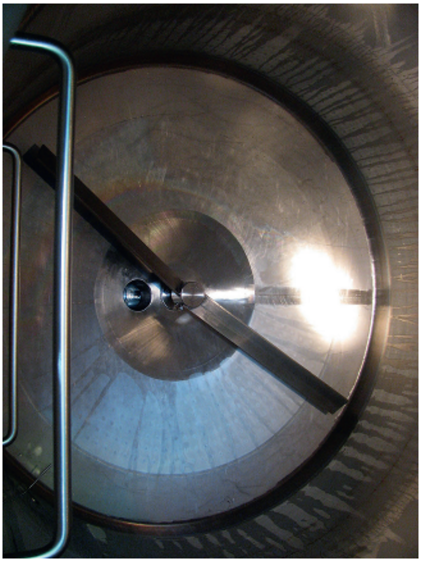

Figure 1.3 Inside the mash tun at Victory Brewing Company. *Source*: Photo by Naomi Hampson.

derived from malt, and the **pH** of mashing have a decisive effect on the character of the beer. The fractions of unfermentable and fermentable carbohydrates in the wort are determined during mashing. The generation of more fermentable sugars results in a thinner, dryer beer with more alcohol. A mash with less fermentable sugars leads to less alcohol but more body and texture.

Wort Separation

After mashing, the wort, the insoluble material, and the split hulls remain in a **slurry**. Wort separation is required to obtain clear wort. The solids remaining after separation are called **draff** or spent grain. Two methods of wort separation are in common use. The more popular is the lauter [*Ger: clear, pure*] process. In this process, the solids are supported on a perforated **false bottom** above the true bottom of the vessel. Here, the grain bed provides filtration, separating the wort from the spent grain. At the beginning of wort separation, wort is recirculated to the top of the vessel. Recirculation, called **vorlauf** [*Ger: forerun*], is maintained until the wort runs clear, indicating the grain bed is established. If the mash and lauter are accomplished in the same vessel, it is called a mash/lauter tun. If the mash and lauter take place in separate vessels, then the entire mash, including liquids and solids, is pumped into a second dedicated vessel called the lauter tun (Figure 1.4). A large lauter tun is equipped with knives or rakes that can slowly dig into the grain bed to increase

Figure 1.4 Lauter tun at Victory Brewing, Parkesburg, PA. *Source*: Photo by Naomi Hampson.

Figure 1.5 Mash filter at Bonesaw Brewing, Glassboro, NJ. *Source*: Photo by Naomi Hampson.

the filtration speed as needed. A different wort separation device, less common in small breweries, is the **mash filter**. Here, the entire mash, including liquids and solids, is pumped into compartments from which the liquid is driven by pressure through filter cloths supported by plates. Figure 1.5 shows a mash filter. Under the filter plates, a conveyor belt for spent grain is visible.

Figure 1.6 Brew kettle at Bonesaw Brewing showing internal calandria. *Source*: Photo by Naomi Hampson.

Boiling

The clarified wort is sent to a vessel called a brew kettle, also called a copper or a wort boiler, and heated to boiling. Figure 1.6 shows a kettle that is heated by an internal **calandria**. Technical issues about wort boiling are discussed in Chapter 9. The wort is usually boiled for 60–90 minutes with evaporation of up to 20% of the wort volume. Boiling consumes the most energy of any step of the brewing process. Hops or hop products are generally added before or during boiling, often in stages so that different portions of the hops are subjected to different boiling durations. Boiling serves several purposes, including the following:

- **Isomerization** of hop compounds for bitterness.
- Sterilization.
- Dissipation of **off-flavors**.
- Removal of proteins and lipids that affect beer clarity and stability.
- Concentration of wort.

Wort Clarification

Boiling generates solid material called hot break or trub. Excessive hot break entering the chiller can clog it or interfere with cleaning it. The hot break material is removed before chilling, either by allowing it to settle (**sedimentation**) or by processing in a vessel called a whirlpool, where the wort is made to move in a horizontal circular pattern to drive the solids into a compact mound at the bottom center of the vessel. In some breweries, the kettle itself also serves as the whirlpool.

Figure 1.7 Chiller at Philadelphia Brewing Company. *Source*: Photo by Marcy Barth.

Wort Chilling

Before fermentation, the temperature of the wort must be lowered from near boiling (100 °C or 212 °F) to the fermentation temperature (typically 9–20 °C or 48–68 °F), a process called wort chilling. The standard device for wort chilling is a **countercurrent** plate **heat exchanger** (Figure 1.7). In some traditional breweries, the hot wort is transferred to a wide, shallow, open vessel called a **coolship**, where it cools slowly by contact with the air. A few breweries use this method to capture wild **bacteria** and yeast, but most brewers prefer a closed chiller to avoid the risk of contamination.

Knockout

Cooled wort from the chiller is transferred to a fermenter, also called a fermentation vessel (**FV**). A selected strain of yeast is added as the wort exits the chiller; oxygen is also added as a nutrient for the yeast. The combined operation of moving the wort from the kettle through the chiller, adding yeast and oxygen, and running the beer into the fermenter is called **knockout**.

Fermentation

The most widely used configuration for the fermenter is the **cylindroconical** vessel (CCV), shown in Figure 1.8. During fermentation, yeast converts certain sugars to ethanol and carbon dioxide to provide cellular energy, but the

Figure 1.8 Cylindroconical fermentation vessels at Susquehanna Brewing Company, Pittston, PA. *Source*: Photo by Naomi Hampson.

process is exploited by brewers to make beer. The overall reaction is $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. In addition to the main reaction, fermentation is accompanied by various side reactions whose products can affect the flavor profile of the beer. The types and amounts of flavor-active side products depend strongly on the fermentation temperature and time, the species and strain of yeast, and the presence or absence of bacteria. The fermentation reaction generates heat, so fermenters usually provide for cooling.

Beer that is fermented at a temperature higher than 15 °C (59 °F) is classified as ale. Ale is usually fermented with a species of yeast called *S. cerevisiae*, also called top-fermenting yeast. Beer fermented at lower temperature is lager beer, usually made with a species called *S. pastorianus* (formerly called *S. carlsbergensis*), also called bottom fermenting yeast.

Conditioning

After fermentation, the new beer, called **ruh beer**, or **green beer**, is held in contact with the yeast for a period that can be as short as a few days for a low-strength ale to as long as several months for some styles. This is the first part of the conditioning process, sometimes called **secondary fermentation**. In lager beer, the secondary fermentation is called lagering. During this period, the flavor of the beer matures, mainly because the yeast absorbs off-flavor compounds. This part of conditioning can take place in the original fermenter or in a dedicated conditioning vessel. Once flavor maturation is achieved, the beer is cooled, which facilitates separation of yeast and clarification of the beer.

Clarification

Beer is often, but not always, subjected to one or more clarification processes. Materials called finings may be added to beer to bind and remove **haze**-forming compounds. The beer may be kept in a tank to allow solids to sediment. It may be clarified in a **centrifuge**. It may be filtered, often through a bed of **diatomaceous earth** (DE) or **cellulose**-containing membranes. It may be treated for **microbial** stability before packaging by filtering out microbes or before or after packaging by a heat treatment called **pasteurization**.

After filtration, the beer is pumped into the bright beer tank, so named because the beer at this stage is typically free of yeast and haze, that is, it is bright. Usually carbon dioxide is dosed into the beer, either in the bright beer tank or in the line to the packaging unit, to provide characteristic carbonation. At this point, the beer is ready to be served directly from the bright beer tanks or to be packaged in kegs, bottles, or cans.

Packaging

The major purpose of beer packaging is to protect the beer quality until it is served. Beer must be kept under pressure to maintain carbonation. Light and oxygen must be excluded to avoid (or at least defer) the development of off-flavors. **Small pack** refers to packaging that is intended for single servings or direct consumer use. Standard small packaging is aluminum cans and **glass** bottles. The other type of packaging is kegs and **casks** (Figure 1.9). Kegs typically contain 50 L or 15.5 US gallons (58.7 L), although smaller

Figure 1.9 Kegs (straight-sided vessels) and casks at Philadelphia Brewing.
Source: Photo by Marcy Barth.

sizes are available. Casks usually contain 40.9 L or one firkin (9 imperial gal). Casks and kegs are used to serve beer on draft where large volumes of a particular brand of beer will be dispensed. The handling of the beer and the packaging process are designed to minimize oxygen entry, as oxygen causes staleness and related off-flavors in beer. Because air is 20% oxygen by volume, the requirement to exclude oxygen during packaging is technically demanding. The packages are purged with carbon dioxide before and after filling and are sealed within seconds.

Serving

Beer service can be as simple as handing the customer a bottle or can, but the usual expectation is that the beer will be delivered in a beer-clean glass. Glasses for beer must be extraordinarily clean. Small traces of **fats** found on nominally clean glassware can interfere with the desirable appearance of the **head** of foam. For this reason, special procedures are needed for cleaning beer glasses. In addition, the beer must be served at the proper temperature and with the correct presentation of foam. The elaborate rituals in some establishments for wine service are trivial in comparison to the routine requirements for serving beer. Beer is often held under pressure in bulk containers, and transmitted through tubing called a **beer line** to a dispensing valve called a beer **faucet**. Beer served on tap from casks or kegs is called **draft** or draught beer. Beer from kegs, but not casks, is often dispensed via gas pressure, usually carbon dioxide.

1.3 A SCIENTIFIC HISTORY OF BREWING

The word *beer* may derive from the Latin verb *bibere*, which means "to drink." But what is the true definition of beer? A modern, Western culture definition of beer might be an alcoholic beverage produced from malted cereal grain, flavored with hops, and produced through fermentation. But to consider the history of beer, the use of this modern definition severely limits our scope of understanding. By requiring the use of "malted grains" and "hops," we limit the historical context from which modern beer descended. These are the major ingredients in modern European-style beer, but not necessarily in all beer. Recall from Section 1.1 that brewing beer requires the conversion of starch into a fermentable sugar. Therefore, a more appropriate, historically accurate definition of beer is "an alcoholic beverage derived from a source of starch without alcohol enrichment." This seemingly simple definition of beer covers the breadth of alcoholic beverages indigenous to regions across the world, local beers that can vary widely from the modern European-style beer with which we are familiar (Table 1.2).

TABLE 1.2 Traditional Beers from Around the World

Beer	Country	Description
Aca	Peru	Maize beer
Bilbil	Ancient Egypt	Sorghum beer, also known as Indian millet
Bi-se-bar	Ancient Sumeria	Light barley beer
Boza	Ancient Babylonia and Egypt	Millet beer
Chi	India	Millet beer
Chibuku	Southeastern Africa	Sorghum beer, also made with maize and millet
Chicha	South and Central America	Maize beer, also made with quinoa, peanut, cassava, palm fruit, or potato
Chiu	China	Wheat beer
Dolo	Burkina Faso, Africa	Millet or sorghum beer, flavored with sisal, castor oil, cassia, pimento, and tobacco
Kaffir	Southern Africa	Sorghum beer
Kava	Polynesia	Dried roots of the *Piper methysticum* tree are chewed, spat, and fermented
Kvass	Russia	Low alcoholic beer made by fermenting rye bread
Maltøl	Norway	Farmhouse beer brewed with kveik yeast
Okolehao	Hawaii	Fermented ti root
Pachwai	India	Rice beer
Pulque	Mexico; Central America	Fermented juice of maguey agave cactus
Sake	Japan	Rice beer saccharified with *koji* mold
Tiswin	North America	Maize beer

Origins of Beer

The origins of beer lie in prehistory. In the absence of written history, we must rely upon the artifacts revealed by archaeology. Presumably, Paleolithic (Old Stone Age) humans experienced an otherworldly euphoria after accidentally eating fermented fruit or drink with mind-altering effects both captivating and terrifying. But when did humans learn to harness the power of fermentation? The earliest written documents display familiarity with beer, indicating that beer was brewed before there was a written language.

There are three requirements for large-scale beer-making. First, there must be a means to grow and process fermentable grains in quantity. Second, there must be a controllable source of heat. Finally, there must be appropriate brewing vessels for heating and fermentation, such as pottery. In the Middle East region, pottery is believed to have been invented around 8500 years ago. The domestication of plants and animals was first undertaken about 12 500 years ago in the *Fertile Crescent*, a region spanning the Middle East from the Persian Gulf through Iran, Iraq, Syria, Lebanon, Jordan, and Israel to northern Egypt. Agriculture made it possible for the land to support larger communities, then cities.

The first chemical evidence of barley beer, consisting of deposits of oxalic acid (**beer stone**) in pottery jars, comes from a 5500-year-old Bronze Age village called Godin Tepe in present-day Iran. Earlier evidence of a mixed fruit, grain, and honey beverage was discovered as residue in pottery from Jiahu in north central China, dating to 9000 years ago. In 2018, analysis of several 13 000-year-old microscopic starch granules recovered from stone mortars in a burial cave at Mount Carmel in northwestern Israel suggested that the mortars had been used to make beer. This interpretation of the evidence is disputed. If further study confirms these preliminary findings, the horizon for beer will have receded to the Paleolithic Age (Old Stone Age), showing that beer was brewed (presumably on a small scale) even before grains were cultivated as an agricultural product.

Fermentation and Science

Beer and other fermented beverages have played a central role in science and technology. Because alcoholic products were embedded in societies across the world, particularly in Europe, economic pressures for consistency and reliability were central to economic success, prompting serious study and innovation. In the 1700s, commercial innovations such as cast iron kettles, steam for heating, the **thermometer**, and the **hydrometer** were directly due to the brewing industry. Steam engines were used in brewing before they were used in weaving.

The science behind the process of fermentation was not described until 1789. The process of making alcohol from sugar was simply referred to as the "putrefaction of sugar." In 1697, Georg Ernst Stahl (1659–1734), the founder of the discredited phlogiston theory of combustion, postulated that the violent activity and heat generation associated with fermentation caused a "loosening" of particles present in the medium; thus, the formation of alcohol was simply a process of separation. The microscopic nature of yeast cells was first recorded by Antonie van Leeuwenhoek (1632–1723) in 1680 after examination of fermenting beer, but the role of yeast in fermentation was still unknown. Yeast was considered a "carrier of activity," participating in, but not responsible for, the separation of alcohol during putrefaction.

The alchemy theory of fermentation held firm until 1789 when Antoine Lavoisier (1743–1794), the founder of modern chemistry, realized that during fermentation, sugar was directly converted to carbon dioxide and ethanol. He performed an **elemental** analysis of sugar, alcohol, and yeast. Significantly, he measured 19% nitrogen in dry yeast. Lavoisier considered fermentation to be a separation of sugar into two parts: one was carbon dioxide, an oxidized compound; and the other was ethanol, a reduced (deoxygenated) compound. Lavoisier, being a member of the French nobility, studied fermentation in wine rather than beer. Also, being a nobleman, he was beheaded during the French Revolution.

Around 1803, British chemist John Dalton (1766–1844) put forward the modern atomic theory that serves as the basis for all chemistry today. In the period from 1803 to 1815, French academic chemists Joseph Gay-Lussac (1778–1850) and Louis Thenard (1777–1857) developed improved analytical methods and used them to refine Lavoisier's analysis of fermentation. Nonetheless, the **chemical equation** for fermentation could not be determined until the molecular **formula** of **glucose** was discovered in the 1870s.

In the eighteenth and nineteenth centuries, there was a major controversy in biology, spilling into related chemistry, between the **mechanists** and the **vitalists**. Mechanists held that life processes were governed by the same physical laws as those of inanimate matter. Vitalists held that life possessed a special life force, or *élan vital*, that could not be explained by laws derived from dead matter. Alcoholic fermentation served as a weapon for both sides of the controversy and, ultimately, was its resolution. One argument favoring **vitalism** was that compounds that only occurred in living organisms could not be made in the laboratory from dead matter. In 1828, Friedrich Wöhler (1800–1882) delivered a setback to this idea by synthesizing urea, an **organic** substance, from ammonium cyanate, considered dead matter. Another piece of evidence for vitalism was that only living organisms were able to make and use *ferments*, which we now call enzymes. In 1833, Anselme Payen (1795–1871) and Jean Peroz (1805–1868) delivered another setback to vitalism by precipitating **amylase** (which they called **diastase**) from barley malt. They demonstrated that isolated diastase could hydrolyze starch. Several other enzymes were found shortly thereafter. The vitalists then made a distinction between *simple ferment* that catalyzes simple hydrolysis reactions and *organized ferment* that is alive and responsible for complex reactions in organisms.

In the 1830s, improvements in light **microscopes** paved the way for the study of fermentation as a biological process. From 1836 to 1838, Charles Cagniard de la Tour (1777–1859), Friedrich Traugott Kützing (1807–1893), and Theodor Schwann (1810–1882) used microscopes to demonstrate that yeast is a living organism and is required for fermentation. These contributions are often mistakenly attributed to Louis Pasteur. The great chemists of the nineteenth century such as Justus von Liebig (1803–1873), Friedrich Wöhler (1800–1882), and Jöns Jacob Berzelius (1779–1848) vehemently opposed and ridiculed the idea that fermentation was a life process, even at first rejecting evidence that yeast was a living organism. Their arguments were implausible and their experimental evidence was nonexistent. Nonetheless, the weight of their authority set the field of biochemistry back by two decades. Ironically, 60 years later, fermentation was achieved without intact yeast cells (but with a yeast extract).

Another argument against the mechanist approach was the optical rotation of light by compounds. Certain compounds in solution, all of which originate in living organisms, are *optically active*; they can rotate a plane of polarized light. The same compounds, when prepared synthetically, do not rotate light. The first major insight into this phenomenon came in 1847 from the graduate thesis of Louis Pasteur (1822–1895). Pasteur separated synthetic sodium ammonium tartrate into two fractions: one of which rotated polarized light to the left and the other rotated it to the right. This showed that optically active compounds can exist in two forms: right- and left-handed. Living systems can selectively make one of these, but synthetic methods invariably make a mixture of both. This difference still has no generally accepted explanation. It may have been this issue that led Pasteur, whose training was in chemistry and physics, to become a founder of the field of microbiology.

Pasteur was an outstanding experimentalist. He established that fermentation carried out by different microorganisms produces different products, usually giving off-flavors to beer and wine. He convinced English brewers to get microscopes to monitor the quality of their yeast. Pasteur regarded fermentation as life without oxygen. He rediscovered the process of pasteurization (first documented in Japan in 1569) for the reduction of microbial load in wine and beer. Ultimately, his experiments reduced the fermentation theories of the German chemists to rubble. He further argued that fermentation is not possible without life. But like Liebig, Wöhler, and Berzelius, Pasteur would be proven wrong; alcoholic fermentation can occur without live cells, given the right enzymes.

The final blow to vitalism, cell-free fermentation, was discovered by lucky accident in 1887 by Eduard Buchner (1860–1917). While developing methods for an entirely different project, he ground several kilograms of brewer's yeast in a large mortar with fine quartz powder as an abrasive. He wrapped the resulting paste in cloth and pressed it in a hydraulic press. Buchner called the resulting cell-free liquid *press juice*. Today, we call it *yeast extract* or *lysate*. Sugar was added to the lysate to suppress the growth of bacteria. Afterward, Buchner noticed the formation of bubbles, which he correctly interpreted as fermentation of the sugar by an enzyme in the yeast lysate. He called this enzyme *zymase*. We now know that there are 12 enzymes involved. Evidently, these enzymes produced by yeast performed this reaction independently of the live cells. Fermentation was carried out by isolated enzymes in the same way as Payen and Peroz carried out starch hydrolysis. No mysterious *élan vital* was needed. Importantly, Buchner demonstrated that fermentation could be studied by the ordinary methods of chemistry and biology.

Building upon Buchner's discoveries, Arthur Harden (1865–1940) discovered that **phosphate** is a requirement of fermentation. In another key experiment, Harden separated yeast extract into a protein fraction that would not go through a membrane and nonprotein fraction, which Harden called *coferment*, that did pass through the membrane. Fermentation required both fractions. We now identify *coferment* as **NAD^+** a key molecule responsible for the transfer of hydrogen in cells. This discovery led to an understanding of the role of **ATP** as energy currency. The discovery of NAD^+ also led to a revolution in the understanding of biological oxidation processes. One of the factors that contributed to this progress was the discovery that the fermentation reactions are identical to those occurring in muscles when oxygen is not available. Muscles turn chemical energy into mechanical work, making them useful for tracking energy. In 1934, the link between fermentation and ATP production was identified. By 1938, the fermentation reactions, now called the **glycolysis** pathway, had been revealed, although some of the enzymes had not yet been isolated. It was not until 1941 that the role of ATP as energy currency was proposed. Many outstanding scientists made decisive contributions to elucidating glycolysis, the first complete biochemical pathway to be revealed. Glycolysis is often called the Embden–Meyerhof–Parnas pathway after three of its discoverers, Gustav Georg Embden (1874–1933), Otto Fritz Meyerhof (1884–1951), and Jakub Karol Parnas (1884–1949). Glycolysis in some form occurs in every living cell. It could be said that the discipline of biochemistry was born in a glass of beer.

The Scientific Method

Today, brewing is a scientific process. The term *science* is derived from the Latin word *scientia*, meaning "to know." The scientific method is a systematic way of thinking about and investigating processes to generate new knowledge. In academic science, this might be the discovery of new enzymes and applications, the development of new hop varieties, or the engineering of a new aeration device. In these examples, new information or new knowledge is generated. In brewing, this might be problem-solving or troubleshooting, in which needed information is identified and new information is sought to help correct an issue.

Scientists must take a systematic and logical approach to generate new knowledge. Often the observations made, the questions posed, and the experiments designed require creativity from the scientist, an ability to think outside of the box. The process is creative, but the approach must be systematic.

The scientific method involves six steps:

1. Make an observation.
2. Pose a question.
3. Generate a **hypothesis** and testable prediction.
4. Design and run an experiment. Record results.
5. Analyze the data. Determine whether it supports or refutes the hypothesis.
6. Repeat the process as needed to further support or refute the hypothesis.

The steps involved in troubleshooting an issue in the brewery provide an example of the scientific method.

1. *Make an observation*. You have noticed that fermentation stalled in the brewery. Most beers finish at 3 °P but this beer stopped fermenting at 6 °P.
2. *Pose a question*. Why did fermentation stall?
3. *Generate a hypothesis and testable prediction*. In this example, the hypothesis is "Fermentation stalled because there were not enough yeast cells." A hypothesis is a testable statement. It must also be

rational and based on well-established facts. A prediction is a deductive consequence of a hypothesis, typically an "if, then" statement. The prediction is "If too few yeast cells were pitched before fermentation, then the fermentation will stall." It is important to recognize that the hypothesis may or may not be correct. It may be necessary to develop a new or revised hypothesis. With appropriate experimentation and analysis, we can decide whether the hypothesis is supported or refuted.

4. *Design an experiment, run the experiment, record results and observations as the experiment proceeds*. In this example, for a subsequent brew, we triple check that yeast is pitched at the appropriate rate ensuring that there are enough cells for fermentation.
5. *Analyze the data*. If the fermentation stalls again, the hypothesis is incorrect or refuted. Some process changes other than cell count affected fermentation. If the fermentation is now completed as normal, the hypothesis is supported.
6. Repeat the process to further support or refute the hypothesis. The results from a test never "prove" an idea as correct but rather "support the hypothesis." On the other hand, if a test fails and refutes the hypothesis, then a new hypothesis and experiment are proposed. Suppose that after ensuring a proper yeast count, the fermentation stalls again. In this case, the hypothesis is refuted, and additional hypotheses are generated. What are some other issues that may cause fermentation to stall? The scientific method and the process of troubleshooting may require several cycles of hypothesis and experiment to move closer to a solution.

For many problems, there are multiple plausible explanations for the issue. After generating additional hypotheses and possibilities, scientists need to prioritize which ideas should be tested. Unfortunately, time and money typically are major limitations to the most thorough testing, especially in a production environment such as a brewery. Therefore, scientists must test the most probable hypotheses while also considering good experimental design.

Good experimental design requires the following:

- A *testable* hypothesis.
- One or more dependent variables.
- Only *one* independent variable or change.
- Experimental controls.
- Statistical significance.

If a hypothesis cannot be tested, it cannot be supported by evidence. For an experiment to serve as a test of a hypothesis, the outcome of the experiment is measured. This is called the dependent variable. In the stalled fermentation experiment described above, the dependent variable is the measurement of the wort density during fermentation. Other measurements, or dependent variables, that might be taken during this experiment are yeast cell count in suspension, carbon dioxide production, and pH.

The independent variable describes what is being manipulated or changed in the experiment. In the stalled fermentation experiment described above, the independent variable is the yeast count in the pitch. It is the only parameter being changed or manipulated. A successful scientific experiment must have only one independent variable. This also applies when troubleshooting a problem. The use of a single variable is critical because if several variables are changed, how will we know which was responsible? To troubleshoot a problem, brewers might try to fix an issue by changing four conditions. While the problem may be solved, how will they learn from the problem and prevent its occurrence in the future? The exact cause of the issue is still unidentified because of a poorly designed experiment. In experimentation or troubleshooting, only change one variable at a time.

A well-designed experiment must be controlled. In typical experiments, an *experimental group* would get various levels of a certain treatment, and a *negative control group* would not get the treatment being tested, but its treatment would be otherwise identical. The two groups are compared to determine the effect of the treatment. In some experiments, it is useful also to include a *positive control*, which is a treatment known to influence the dependent variable. If the positive control fails to yield the expected result, we suspect that there is something wrong with the experiment. For example, we might study whether the addition of zinc chloride increases the fermentation rate. We would set up several flasks with identical wort composition. To the experimental group, we could add various concentrations of zinc chloride solution, but to the negative control group, we could add an equal amount of pure water. The positive control group could be treated with yeast nutrient, known from previous experiments to increase the fermentation rate. We place all the flasks in baths at the same temperature. We add the same amount of the same yeast to each flask. We do all we can to make sure that the experimental group and the two control groups are treated identically except for the independent variable, zinc chloride. If the positive control flasks do not ferment faster than the negative control flasks, we would suspect that there is something wrong with the way the experiment was run. Maybe there was a leak, or the yeast was not good. If the zinc chloride flasks differ from the negative control flasks, that would be evidence that zinc chloride influences the fermentation rate.

In addition to control groups in an experiment, good experimental design includes a tightly controlled environment. Every condition of the experiment, other than the independent variable, should be kept as precisely consistent as possible. In studying the effect of zinc chloride on fermentation, what are some of the environmental controls? This experiment is best controlled by running all experiments at the same time, using the same wort, and at the same temperature. The list continues, but the point is that only the independent variable should be different. Any other difference could influence or change the results. Eliminating uncontrolled variables in laboratory-scale experiments can be difficult, but it is much more difficult in practical settings like a brewery where time, space, and money are limited.

During experimentation, scientists gather data, interpret results, and formulate conclusions. For an experiment to be significant, it must have some type of statistical probability of being correct, and it must be repeatable by the original experimenters and by others. An experiment that was run only once has dubious validity. Many measurements rely on a representative sample. If, for example, you were checking package oxygen, you could only test a small fraction of the bottles or cans. If you tested them all, you would have no beer to sell. The packages selected for testing are the *sample*. For a sample to be representative, it must be random. If you select 15 bottles in a row as they emerge from the filler, you may miss a problem that emerges later in the run or that is intermittent. If you pick the whole sample from one side of the conveyor, you may introduce a bias into the sample that could affect the conclusion. Here, it is best to select a representative sample of bottles randomly throughout the production run from start to finish.

The other sampling issue is sample size. Larger samples more closely represent the entire population, but they are more expensive in terms of analysis cost and lost beer. To illustrate the effect of sample size, we will use an artificial example involving a large bin of glass marbles, 60% of which are red and the rest blue. Figure 1.10 shows the total percentage of red marbles as we randomly draw marbles one by one. It takes over 100 draws to reach a steady-state value near 60%. Larger sample sizes give more trustworthy results, but even for a large sample, the outcome is subject to error. In scientific usage, the word "error" refers to the difference between the accepted, "true," or expected value and the measured value. "Error" does not imply that anyone did anything wrong.

Throughout this book, you will have an opportunity to apply the scientific process by troubleshooting potential problems in the brewery. Case studies are provided in select chapters to help you think critically about problems that may arise in the brewing process and to propose potential solutions. The ability to troubleshoot by thinking scientifically about problems is one of the greatest skills you can bring to any job.

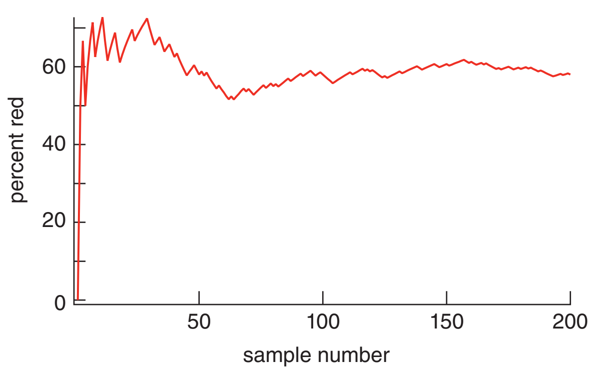

Figure 1.10 Cumulative outcomes of marble draws.

1.4 INTRODUCTION TO BEER QUALITY

It is often said that a glass of beer is best at the source. This is unfortunately true; beer is a perishable product whose quality slowly diminishes with time after production. As brewers, our goal is to provide as close to "brewery fresh" beer as possible to all consumers whether on draft at the brewery or at home from a bottle or can. With increasing competition in the brewing industry comes a need for consistency and quality product for the consumer. If we want to provide fresh and high-quality beer to the consumer, we must first define quality.

In 2014, a Brewers Association subcommittee on quality defined quality beer as ". . .a beer that is responsibly produced using wholesome ingredients, consistent brewing techniques, and good manufacturing practices, which exhibits flavor characteristics that are consistently aligned with both the brewer's and beer drinkers' expectations." This definition emphasizes consistency, responsibility, and safety. To make quality beer, a brewer must master the brewing process, have a deep familiarity with the raw materials, and have a solid understanding of the underlying science.

Mary Pellettieri (cited in the Bibliography) lays out three fundamental aspects of beer quality that take the definition of quality one step further. First, beer should be free from **defect**. Second, beer should be fit for use in the sense that it meets the expectations of consumers. Third, beer quality should match the brand values of the company; that is, the artistic side of brewing also represents quality.

Quality as Freedom from Defect

Freedom from defect is defined by laws and government regulations. The best-known historical food safety and quality government regulation was the Bavarian ***Reinheitsgebot*** or German Purity Law, decreed in 1516. Although not the first such regulation, it was the first to cover more than a single city. Still influential today, this law placed strict specifications on the production of beer, allowing only three ingredients—barley, hops, and water. The fourth ingredient, yeast, is now included in the law, but was absent in the original, because yeast was not understood as the causative agent of fermentation until the nineteenth century. It is thought that the purity law was put into place because some German brewers used alternatives to hops, such as **gruit**, and alternative cereal grains such as wheat and rye. At the time, brewers were taxed on malt and not on beer produced, so crafty brewers could skirt taxation by brewing with alternative sources of starch. Furthermore, the use of wheat and rye depleted the supply for the baking industry; thus, the *Reinheitsgebot* protected the German economy. The far-reaching impact was to define a specific flavor profile for German beer with a traditional standard of quality still held in high esteem in Germany today.

Beer quality as freedom from defect has evolved in the United States over the years. Today, beer is defined as a food, and breweries are required by law to produce products that are free from defects. These laws are designed to protect consumer safety. US laws require four specific parameters to define beer as free from defects:

1. The Tax and Trade Bureau (TTB) requires accurate reporting of fill levels in bottles and cans.
2. The TTB also requires accurate reporting of **alcohol by volume** (ABV) to within 0.3% if printed on labels.
3. The US Food and Drug Administration (FDA) requires sulfite concentrations to be less than 10 parts per million (ppm), unless specifically reported on the label.
4. US breweries are now required by the Food Safety Modernization Act, administered by the FDA, to follow good manufacturing practices (GMPs) with strong recommendations for a hazard analysis and critical control points (**HACCP**) plan. GMPs provide safety standards for the facility, employees, and visitors to help ensure that products are free from defects. HACCP is a system of risk assessment that evaluates risk potential across all production processes with a focus on chemical, physical, and biological risks.

Quality as Fitness for Use

“Fitness for use” describes quality from the perspective of the consumer. These are the traits that drive a particular beer or brand. Establishing a definition of quality as fitness for use emphasizes consumer preferences. Often the consumers’ preferences are less stringent than the brewer’s. For example, variation in slight to moderate haze might be perceptible, but otherwise disregarded by the general consumer population. By contrast, if a slight haze is accompanied by large particles of protein that sink to the bottom of the glass, consumer opinion of quality may plummet. If consumer perception of quality dips into unfavorable territory, the brewery will lose customers. If you consistently produce beers with high quality in fitness for use, consumers will know what to expect in your product, potentially building brand loyalty. Those traits commonly defined under fitness for use include flavor, shelf stability, and aspects of perception like color, clarity, and foam. Understanding these traits, how they are influenced by the brewing process, and how they can change over time in finished beer is essential for the delivery of a high-quality product.

For each beer, a brewery should describe these traits as being “true to type.” Being true to type means that, for a given brand and style of beer, each production lot of that beer is as similar as possible. Key aspects of the beer such as appearance and flavor should be considered before a beer is released to market. Any defects or deviations should be subject to troubleshooting and root-cause analysis.

Appearance Consumers first drink with their eyes. Appearance, or the physical qualities of the beer, makes the first impression and can underlie the overall reception of the beer. Beer should always be poured into an appropriate and clean glass to fully appreciate these qualities. Drinking directly from a bottle or can obscures judgment (which in some cases might be intentional). Specifically, a number of metrics play key roles in the overall physical quality and perception of the beer, metrics that influence the overall **organoleptic** quality of beer, specifically color, clarity, foam, aroma, and texture.

Color—Beer color can range from light yellow to black with varying shades of red. Generally, beer color should be appropriate to the style. A 2017 study demonstrated that when two identical beers are artificially colored so that one resembles a pale beer and the other a dark beer, significant differences were found in consumers' expectations of flavor and cost.

Clarity—Bright or clear beer is highly prized. Significant effort during production ensures a consistently clear product. Nonetheless, some styles such as wheat beers, hefeweizens, and New England IPAs are designed to be hazy. In addition to physical appearance, haze, also called **turbidity**, can alter the flavor profile of the beer. Beer haze generally results from aggregates of protein from barley and **polyphenols** from hops. Hazy IPAs are said to be more flavorful than their clarified counterparts. It has been demonstrated that certain hop oils with low solubility are stabilized within haze particles, keeping them in solution and thus changing the profile of the product. This observation also explains why flavor profiles of beer can be altered following filtration. The consistent haze found in certain styles is also called permanent haze. **Chill haze** is a quality issue where haze particles are formed at cold temperatures but disperse as the beer warms. Chill haze that becomes worse over time is referred to as age-dependent haze.

Foam—Beer is expected to have an attractive layer of foam, or head, that persists during drinking. As the beer is consumed, **lace** or cling should gently coat the sides of the glass. Foam enhances aroma as **volatile** compounds are released as effervescence when the foam bubbles pop. Foam also enhances the texture of the beer and has been shown to dampen the waves in the beer, so it is less likely to spill.

Aroma—The aroma of beer is heavily influenced by raw material selection, process, and handling of the beer. Service temperature and carbonation level also influence aroma and consumer perception.

Texture—Beer provides different tactile sensations, typically sensed by the trigeminal nerve. The trigeminal nerve is the main sensory nerve of the head, innervating the face, mouth, and nasal cavity. It is responsible for sensations of heat from peppers, the burn from alcohol, and the fizz from carbonation. Beer is described as dry (thin) or full-bodied, traits that are related to the residual carbohydrate content of the beer remaining after fermentation.

Flavor Flavor is the greatest factor in consumer expectations. It might also be considered an element of perception, and its impact on overall organoleptic quality places it in high importance. A beer might look appetizing, but if it tastes bad, the brewery's reputation is at risk. Beer flavor is a complex synergy of more than a thousand compounds that derive from raw materials and the overall process. Some flavors are dominant and distinguishable in isolation, but others fall below the limit of individual perception. Some flavors arise only as combinations of multiple lesser flavors that would be difficult to distinguish alone. To further complicate the issue, perception of flavor varies greatly between individuals, as different people can discern different concentrations of key flavor molecules.

In the brewery, flavors should always be matched as true to type. Flavors not characteristic of a style are considered off-flavors. Off-flavors arise from variations in raw materials, process, or microbial contamination. They also develop over time as a beer ages, a process known as **staling**. A beer's exposure to oxygen, high temperatures, and mechanical agitation all affect the flavor stability of a product.

Stability Beer flavor will start to decline the moment it leaves the brewery. Beer served at a brewery taproom can be easily controlled, but once it leaves the brewery in a package, its quality is much more difficult to manage. In addition, the chemical processes that create staling off-flavors develop more quickly with heat. For this reason, beer has a typical shelf life of six to eight months when kept refrigerated and shorter if kept at room temperature or heated during summer months. Beer stability will depend on the process and also on the style. Stale beer does not have one single characteristic flavor but rather a suite of off-flavors depending on the style, age, and handling.

As a beer ages, hop bitterness and flavor decline steadily. Key **esters** may be reduced. The breakdown of **free amino nitrogen** (FAN) via Strecker degradation can create off-flavors such as sweetness with unpleasant notes of floral, toffee, meat, or bourbon. Oxidation leads to sherry-like aromas and ultimately cardboard flavors. As hop compounds oxidize, they yield **ribes** aromas, often described as catty, tomato leaves, or blackcurrant. The oxidation of lipids leads to the formation of cardboard or paper flavors. Once oxidation and flavor staling occur, there is no recovery. To forestall staling, best brewing practices minimize oxygen uptake throughout the brewing process, including packaging, to prolong beer stability. Beer must be kept free from microbial contamination by **wild yeast** and bacteria. Microbial contamination in a packaged product can lead to off-flavors or overcarbonation.

Quality as Art

While adherence to beer quality as freedom from defect is required in all breweries by law, there is more flexibility in quality as fitness for use. But what about the art of brewing? There are certainly small breweries who relish the benefits of being small scale such as faster beer turnover, taproom-only beers, and the ease of innovation. Here, brewers may highly value the opportunity to use new ingredients, to form exciting collaborations, and to push the boundaries of traditional brewing practices. Is there quality in creativity? Absolutely. Here quality as art is defined by how each beer matches the *brand values* of the business. In this case, the leadership team at the brewery should take time and care to define the overall brand values of the business, clearly documenting them and sharing them with all employees. In addition to beers being “true to type,” they should also be “true to brand.” Then as each new product or innovation is planned, the team can assess its compatibility with the overall brand of the company. In this sense, the quality of art and creativity help define the quality of the beer.

BEER QUALITY AND SCHLITZ BEER

At the start of the twentieth century, the Joseph Schlitz Brewing Company (established in Milwaukee, Wisconsin, in 1849) was the largest producer of beer in the United States. Their famous tagline was “The beer that made Milwaukee famous.” At the edge of innovation in the 1970s, Schlitz championed a new production process called accelerated batch fermentation (high-temperature fermentation) to increase yield and improve efficiency. To lower the cost of raw materials, Schlitz substituted corn syrup for some of the malted barley and hop pellets instead of whole hops (a practice that is now widely accepted). Flavor and clarity changed. Clarity issues were resolved by the addition of a clarifier, possibly papain. Then, the foam stability changed. The resulting foam issue was resolved by adding propylene glycol alginate (PGA). These innovations interfered with the flavor and stability of the beer in the market. Looking back on it today, it seems as though a business decision was made to cut costs and to allow the quality to decline in small increments, hoping the consumers would not notice. This approach is derisively called “salami slicing.” On the shelf, an unexpected interaction between the clarifier and the PGA sometimes resulted in the formation of clouds of snowy particles (**bits**) after a few months. Schlitz management was slow to deal with the issue. Customers found the bits to be unacceptable.

The downfall of Schlitz is an unfortunate example of how quality as fitness for use was not given adequate consideration in process changes and innovations to improve efficiency. Furthermore, problem-solving strategies and attention to quality management were seemingly inadequate with the result that poor-quality products entered the market. Ultimately, Schlitz returned to its original recipe, but it was too late. Sales never recovered. The original Schlitz is now produced by Pabst Brewing Company; it has a small but devoted following.

CASE STUDY

A brewery has made the same hefeweizen beer for years. But in the last several production batches, flavor differences have been noted by a series of trained panelists, particularly an increase in isoamyl **acetate** (banana) and an increase in higher alcohols (unpleasant heat from alcohol). In thinking carefully about what changes may have occurred that could have caused the flavor change, the Director of Quality realized a new sound system was recently installed in the brewery. Several speakers and a subwoofer were placed about a meter from the fermentation tanks, and since installation, the staff enjoyed listening to music throughout the day. In reviewing production records and notes from the taste panel, the Quality Director realized that the changes in flavor corresponded to the date of the speaker installation. The Director then tried to explain to the Operations Manager that the music could be affecting fermentation, but the Manager argued that the music was good for employee productivity. The Director then decided to conduct an experiment with four hefeweizen fermentations in the laboratory. Two were subjected to electro-swing music via a waterproof speaker and two were kept in a quiet corner of the laboratory. Fermentation rates were tracked each day by measuring the beer density. When fermentation was complete, the same sensory panel evaluated the flavors in the finished beers. Analysis of the data revealed that the two samples subjected to music fermented faster. They finished fermenting a day sooner, and the sensory panel noted an increase in banana flavor and alcohol burn as compared with the quiet fermentation. These results convinced the Operations Manager to remove the speakers from the fermentation cellar.

CASE STUDY QUESTIONS

1. What was the observation that prompted this scientific experiment? What was the hypothesis? What was the prediction statement?
2. What were the independent and dependent variables?
3. Describe how this experiment was controlled. Are there any other controls you might include in the experiment?
4. How confident are you in the results of this experiment, and why?
5. How could the experiment be improved?

CHECK FOR UNDERSTANDING

1. Compare the legal, commercial, and scientific concepts of beer.
2. How does beer differ from wine and whiskey?

3. Arrange the following brewing processes in order. Give a one-sentence statement of the purpose of each.

Beer Clarification	Boiling	Serving
Conditioning	Mashing	Wort chilling
Fermentation	Milling	Wort clarification
Knockout	Packaging	Wort separation

4. Identify the four major ingredients in beer and describe their roles.
5. What are some advantages of reducing the ratio of total water used to beer produced?
6. Describe the flow of energy into and out of each brewing step.
7. What is the primary purpose of milling?
8. What are three major ways in which packaging preserves beer quality?
9. Explain the positions of the vitalists and mechanists and their evidence.
10. Where and when were the origins of beer?
11. What were the three major technological advances that made routine beer brewing possible?
12. Louis Pasteur is often mistakenly credited with discovering yeast. What were some of the major discoveries about the role of yeast in fermentation? Who made these discoveries?
13. What were some of Louis Pasteur's major contributions to brewing science?
14. What is a controlled experiment?
15. Discuss the difference between an independent and a dependent variable.
16. How can the scientific method be used for brewery troubleshooting?
17. Discuss the scientific understanding of "error."
18. Why is it critical to change only one variable at a time during an experiment or while troubleshooting?
19. What government agencies regulate the beer industry in the United States? By law, what metrics must brewers report?
20. What did the *Reinheitsgebot* permit in beer? What are some common materials used in beer today that would be forbidden by the *Reinheitsgebot?*
21. Discuss the concept of "freedom from defect."
22. What is meant by the phrase "true to type," and how would you incorporate it into a brewery?
23. Explain the concept of "fitness for use." Give examples.

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