We wrote this book to help you to 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? There are legal and marketing definitions, but in a book on brewing science, we will use a scientific definition. Beer is an undistilled alcoholic beverage derived from a source of starch. “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 an enzyme, a substance that guides and speeds up a reaction. Mastering
the science of raw materials and the process steps of beer production is essential to making quality beer. Here, 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. And 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 is often brewed with other ingredients. These can include adjuncts, which are sources of starch or sugar other than malt, and processing aids, which are materials used to help give the beer desirable characteristics. Some common processing aids are finings, which help to clarify the beer; carbon dioxide, which carbonates the beer; foam enhancers, which provide desirable foam properties; and colored materials, which are used to adjust the color of the beer. In this introduction 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. It 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 waste material to dispose of, and less negative impact on the environment. Water itself is a characterless compound of fixed composition. Water supplied to breweries is a mixture with many desirable and undesirable components present in trace amounts. The nature and amount of these trace components is important to the character and quality of the beer. Water is usually processed 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, the source of which is cereal grain. At least some of the grain is ordinarily processed to give malt, a process called malting. Malt is seeds of grain that are germinated and then dried. The most common grain for malting is barley, but wheat, rye, and oat malt are available. Rice and
maize (corn) can be malted, but these malts are strictly specialty items; they are rarely used in beer brewing. Since medieval times, malting has been a separate craft from brewing, and malt is produced in specialized facilities. Brewers need a basic understanding of the malting process to make the most effective use of the available varieties of malt.

Malting begins by cleaning live seeds of grain over a series of sieves. The grain is then steeped (soaked in water) at a controlled temperature, typically in two to three stages of steeping and draining. The grain is then permitted to germinate. It must be kept in contact with air to support respiration and to carry away heat generated by the life processes. The seeds are regularly turned to expose them to oxygen and to maintain a uniform temperature, avoiding hot or cold spots. Regular turning also prevents sprouting roots from becoming tangled. The germination process produces several changes in the seeds, collectively called modification. Enzymes are produced that assist the modification process. Some of these enzymes are also critical to the brewing process in that they are responsible for converting the starch to sugar during mashing. Certain polymers, including proteins and beta-glucan, are hydrolyzed into smaller molecules under the influence of the enzymes. After modification, the seed loses its pebble-like hardness and becomes friable (easily crushed). Some of the starch in the seeds is consumed as fuel to power the life processes of the embryo. This is called malting loss. When the maltster judges that germination has proceeded far enough, the seeds are transferred to an oven, called a kiln, and heated with moving air. Different grades of malt are produced by varying the degree of modification and the temperature and duration of heat treatments. Shorter kiln times at lower temperatures yield malt with more starch-hydrolyzing enzymes and less flavor. Longer, higher temperature kiln treatment yields darker, more highly flavored malts, but with a lower enzyme content. Some malt is subjected to additional heating, called roasting, to give dark, highly flavored but nonenzymatic malt. Chapter 4 covers the malting process in detail.

Hops

The hop is a climbing plant, *Humulus lupulus*. The fruits of the hop plant, hops, are boiled with the beer wort to provide bitterness and other flavors. Hop compounds also have an antibacterial effect that can help preserve the beer. Sometimes hops are added at other points in the brewing process to provide desired flavor effects. There are many varieties of hops with different flavor profiles. In addition, there are products derived from hops that are often used instead of or in addition to the natural hops. Chapter 4 provides details about hops and their processing.
Yeast

Yeast is the 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 character of the beer. Yeast is often cultivated at the brewery. Processes and practices involving yeast are covered in detail in Chapter 9.

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.
- 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 chiller.
- The cool wort is pumped into a fermenter. Yeast is added (pitched).
- After several days of fermentation and conditioning, the yeast is removed from the beer, and the beer is pumped into the bright beer tank. Carbon dioxide is added under pressure.
- The beer is served or packaged.

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.
Figure 1.1 Overview of the brewing process for a four-vessel brew house.
BREWING QUALITY OVERVIEW

**Brew House**

The **brew house** (Figure 1.2) is the facility that makes beer wort out of water, malt, adjuncts, and hops. Brew house operations involve hot water or hot wort, so the brew house is sometimes called the *hot side*. Because one of the last steps in this process is boiling the wort, the brew house presents less of a concern for **microbial spoilage** than the **cellar**. The brew house operations are milling, mashing, **wort separation**, boiling, and chilling.

**Milling** Malt is delivered to breweries in bulk or in bags. Before use in brewing, malt must be crushed into small pieces to extract the starch. The physical operation involved is milling. Crushed grain is called grist. The device

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**TABLE 1.1** Brewing Steps, Durations, and Temperatures

<table>
<thead>
<tr>
<th>Process Step</th>
<th>Duration</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milling</td>
<td>1–2 hours</td>
<td>Ambient</td>
</tr>
<tr>
<td>Mashing</td>
<td>1–2 hours</td>
<td>45–67 °C</td>
</tr>
<tr>
<td>Lautering/sparging</td>
<td>1–2 hours</td>
<td>75–78 °C</td>
</tr>
<tr>
<td>Boiling</td>
<td>1–2 hours</td>
<td>105 °C</td>
</tr>
<tr>
<td>Whirlpool</td>
<td>15–30 minutes</td>
<td>76–74 °C</td>
</tr>
<tr>
<td>Fermentation (ale)</td>
<td>4–10 days</td>
<td>15–25 °C</td>
</tr>
<tr>
<td>Conditioning (ale)</td>
<td>2–14 days</td>
<td>−1 to 6 °C</td>
</tr>
<tr>
<td>Filtration</td>
<td>2–12 hours</td>
<td>2–6 °C</td>
</tr>
<tr>
<td>Packaging</td>
<td>&lt;12 hours</td>
<td>2–6 °C</td>
</tr>
<tr>
<td>Duration of typical shelf life</td>
<td>−6 months</td>
<td>2–6 °C</td>
</tr>
</tbody>
</table>
that performs the operation is a mill (Figure 1.3). 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, also called the testa. Milling breaks open the seed coat and crushes the interior of the seed, producing additional surfaces at which water can react with starch. Milling details have a significant effect on the character of the beer and the efficiency of the process. It is essential that the malt hulls be split but not pulverized. They will aid in a later step, wort separation.

**Mashing** During the mashing step, starch is converted to smaller sugars that brewing yeast can ferment. Yeast cannot ferment starch, so this step is essential. 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 1.4). The mash tun may contain an agitation paddle for gentle mixing. The details of the time–temperature profile, the activities of
enzymes derived from malt, and the pH of mashing have a decisive effect on the character of the beer.

Three processes must occur for effective mashing. The first is gelatinization, in which starch granules absorb water, swell, and burst, giving the starch molecules access to water. Some grains, including barley and wheat, gelatinize readily in the normal mashing temperature range. Others, like maize (corn) and rice, must be cooked in a separate vessel before addition to the mash. The second process is liquefaction, in which starch molecules are hydrolyzed in the interior of the molecular chain to give soluble, but still too large for fermentation, fragments. The third process is saccharification, in which starch chains and fragments are further broken down at the ends of the chains to yield the fermentable sugars: glucose, a monosaccharide; maltose, a disaccharide; and maltotriose, a trisaccharide. Mashing temperature plays a key role in determining the fraction of starch that is liquefied and the fraction of dissolved carbohydrate that is fermentable.

The amounts of unfermentable and fermentable carbohydrates are determined during mashing, influencing the character of the finished beer. 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 broken 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 most popular is the lauter process [Ger: clear, pure]. In this process the solids are supported on a perforated false bottom above the true bottom of the vessel. Liquid is drawn through the grain and the false bottom via valves in the true bottom. The actual filtration is accomplished by the grain bed, the split hulls from the malt. The false bottom supports the grain bed and facilitates separation. In the first minutes 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 set. If the mash and lauter are accomplished in the same vessel, this is called a mash/lauter tun. Often the entire mash, liquids and solids, are pumped into a separate, dedicated vessel called the lauter tun (Figure 1.5). The lauter tun is equipped with knives or rakes that slowly dig into the grain bed to increase the filtration speed. A different lautering 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 filtration material.

During or after lautering, the grain is rinsed with hot water, a process called sparging. Sparging recovers sugar that is held up in the grain bed, so more beer can be made from less grain.

![Figure 1.5](image-url)  A peek into the lauter tun at Urban Village Brewing Company. *Source:* Photo: Dave Goldman.
Boiling  The clarified wort is sent to a vessel called a brew kettle, also called a copper, or a wort boiler (Figure 1.6) and heated to boiling. 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.

Boiling generates solid material called hot break or trub (“troob”). Sometimes the hot break material is removed before chilling, either by allowing it to settle (**sedimentation**) or in a vessel called a whirlpool, in which

![Figure 1.6 Brew kettle at Yuengling Beer Company.](image_url)
the wort is made to move in a horizontal circular pattern that drives the solids into a compact mound at the bottom center of the vessel. In some breweries the kettle itself also serves as the whirlpool.

**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 chilling. The standard equipment for chilling is a **countercurrent** plate heat exchanger. The **unit** consists of a series of closely spaced and parallel heat-conducting plates, as shown in Figure 1.7. The hot wort flows through half of the channels between the plates, and a coolant, typically water or an **antifreeze** mixture, flows through the rest. Each plate has wort on one side and coolant on the other. Typically, the outgoing water, which is now hot, is added to the **hot liquor tank**, to be used for later brewing operations.

In some traditional breweries, the hot wort is drawn into a wide, shallow vessel called a **coolship**, where it is slowly cooled by convection. 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.

At the beginning of fermentation, the yeast needs dissolved oxygen (as a nutrient, not for respiration) to help prepare cell **membranes**. Because the

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**Figure 1.7** Chiller at Philadelphia Brewing Company.
boiling process strips the wort of all dissolved gases and because gases are more soluble at cooler temperatures, oxygen is injected into the wort as it exits the chiller. The oxygen requirement depends on the solids content of the wort and on the strain of yeast.

**Cellar**

Before the days of mechanical refrigeration, fermentation and conditioning were often carried out in an underground room, or even a cave, called the cellar. Figure 1.8 depicts the underground caves at the Yuengling brewery in Pottsville, PA, where beer was formerly lagered and conditioned. Today, fermentation and conditioning temperatures are usually controlled artificially in the tanks themselves, and the “cellar” can be at any level of the brewery. The cellar is sometimes called the cold side.

**Fermentation** Cooled, aerated wort from the chiller is transferred to a fermenter, also called a fermentation vessel (FV). The most widely used configuration for the fermenter is the cylindroconical vessel (CCV), shown in Figure 1.9. A selected strain of yeast is added or pitched into the wort. Fermentation converts certain sugars to ethanol and carbon dioxide. The reaction is carried out by yeast, a single-celled fungus, as a means for the yeast to make cellular energy in the absence of oxygen. Fermentation occurs in 12 distinct steps. The overall reaction is $\text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 2\text{C}_2\text{H}_5\text{OH} + 2\text{CO}_2$. In addition

![Caves at Yuengling Beer Company.](image)
BREWING OVERVIEW

Infermentation is accompanied by a variety of 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, the species and strain of yeast, and the presence of bacteria. The fermentation reaction generates heat, so fermenters usually have provision 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 temperatures is lager beer, usually made with a species called *S. pastorianus*, 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 several months for some types of lager beer. 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.

**Filtration** 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

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**Figure 1.9** Fermentation vessels in the cellar at Susquehanna Brewing Company.
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 after packaging by a heat process called pasteurization.

After filtration, the beer is pumped into the bright beer tank, so named because the beer at this stage is 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 tanks or to be packaged in kegs, bottles, or cans.

Unfiltered beer is common in small breweries that lack filtration equipment. Here beer is chilled after fermentation, carbonated, and served directly. Brewers should make sure that fermentation is complete before packaging unfiltered, unpasteurized beer to avoid the risk of excessive pressure from secondary fermentation.

Packaging

The major purpose of beer packaging is to protect the beer 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. About 2 L (~0.5 US gallon) is considered the upper limit of small pack. Standard small packaging is aluminum cans and glass bottles. Plastic PET bottles are also on the rise. In addition to protecting the beer, small pack has the very important function of enhancing sales. Small pack is invariably decorated with branding material. Bottles are festooned with paper or plastic labels. Some have front labels, back labels, neck labels, and cap covers (often made of foil). Cans, if purchased in quantity, can be preprinted directly on the aluminum. Alternatively, breweries may apply a label or plastic shrink wrap to an unlabeled aluminum can. Bottles and cans are packed in branded secondary packaging such as six packs and cases, usually made of cardboard or plastic.

The other type of packaging is kegs and casks (Figure 1.10). Kegs typically contain 50 L or 15.5 US gallons (58.7 L), although smaller sizes are available. Casks usually contain 40.9 L or 1 firkin (9 imperial gal). Casks and kegs are used to serve beer in bars or at parties where large volumes of a particular brand of beer will be dispensed. A full US-size keg of beer weighs about 73 kg (160 lb); the empty keg alone weighs 13.5 kg (30 lb) (Table 1.2).

The handling of the beer and the packaging process are designed to minimize oxygen entry. Oxygen causes staleness and off-flavors in beer. Because air is 20% oxygen by volume, the requirement to exclude oxygen is technically demanding. The packages are purged with carbon dioxide before and after filling and are sealed within seconds.
The packaging process involves unpacking the containers, rinsing and sanitizing them, conveying them to the filling station, purging out air, filling, and then sealing the packages. Often the beer is pasteurized just before or after packaging or subjected to microbial filtration before packaging. Labels and their adhesives are applied. Secondary packaging is unloaded from its packaging and folded into shape. The filled cans or bottles are gently loaded into the cases, which are then sealed with adhesive and stacked on pallets. The complexity of the packaging operation and its potential for breakdowns rival all the rest of the brewery combined (see Figure 1.11).

### 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 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. 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.

For economics as well as esthetics, beer is often held under pressure in bulk containers, like kegs, transmitted through tubing called a beer line to a dispensing valve called a beer faucet. Beer served from casks or kegs is called draft or draught beer. Although the standards for beer from casks forbid it, beer from kegs is driven from the keg to the tap by gas pressure, usually carbon dioxide. The requirements for keg service include a cold locker for the kegs, pressure tanks and regulators for the driving gas, lines that hold pressure and exclude permeation by oxygen, and faucets. It is often necessary to provide chilling to the beer lines to maintain the proper service temperature and carbonation. The entire system must be amenable to regular and thorough cleaning to maintain beer quality.

1.3 A SCIENTIFIC HISTORY OF BREWING

The word beer is derived 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 for which modern beer was derived. 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.” 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 1.3).

To understand the history of beer, we must rely upon the availability of artifacts and documents. Presumably Paleolithic (Old Stone Age) humans experienced an otherworldly euphoria after accidentally eating fermented fruit or drink, with mind-altering affects both captivating and terrifying. But when did humans learn to harness the power of fermentation? The earliest

### Table 1.3 Traditional Beers from Around the World

<table>
<thead>
<tr>
<th>Beer</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aca</td>
<td>Peru</td>
<td>Maize beer</td>
</tr>
<tr>
<td>Bilbil</td>
<td>Ancient Egypt</td>
<td>Sorghum beer, also known as Indian millet</td>
</tr>
<tr>
<td>Bi-se-bar</td>
<td>Ancient Sumeria</td>
<td>Light barley beer</td>
</tr>
<tr>
<td>Boza</td>
<td>Ancient Babylonia and Egypt</td>
<td>Millet beer</td>
</tr>
<tr>
<td>Chi</td>
<td>India</td>
<td>Millet beer</td>
</tr>
<tr>
<td>Chibuku</td>
<td>Southeastern Africa</td>
<td>Sorghum beer, also made with maize and millet</td>
</tr>
<tr>
<td>Chicha</td>
<td>South and Central America</td>
<td>Maize beer, also made with quinoa, peanut, cassava, palm fruit, or potato</td>
</tr>
<tr>
<td>Chiu</td>
<td>China</td>
<td>Wheat beer</td>
</tr>
<tr>
<td>Dolo</td>
<td>Burkina Faso, Africa</td>
<td>Millet or sorghum beer, flavored with sisal, castor oil, cassia, pimento, and tobacco</td>
</tr>
<tr>
<td>Kaffir</td>
<td>Southern Africa</td>
<td>Sorghum beer</td>
</tr>
<tr>
<td>Kava</td>
<td>Polynesia</td>
<td>Dried roots of the <em>Piper methysticum</em> tree are chewed, spat, and fermented</td>
</tr>
<tr>
<td>Kvas</td>
<td>Russia</td>
<td>Low alcoholic beer made by fermenting rye bread</td>
</tr>
<tr>
<td>Maltøl</td>
<td>Norway</td>
<td>Farmhouse beer brewed with Kveik yeast</td>
</tr>
<tr>
<td>Okolehao</td>
<td>Hawaii</td>
<td>Fermented ti root</td>
</tr>
<tr>
<td>Pachwai</td>
<td>India</td>
<td>Rice beer</td>
</tr>
<tr>
<td>Pulque</td>
<td>Mexico; Central America</td>
<td>Fermented juice of maguey agave cactus</td>
</tr>
<tr>
<td>Tiswin</td>
<td>North America</td>
<td>Maize beer</td>
</tr>
</tbody>
</table>
written documents display familiarity with beer, indicating that beer was being brewed before there was a written language. The origins of beer lie in prehistory.

**Origins of Beer**

The domestication of plants and animals was first undertaken about 12,500 years ago in what was considered the *Fertile Crescent*. This “cradle of civilization” spanned the region of the Middle East from the Persian Gulf to northern Egypt and through Iraq, Syria, Lebanon, Jordan, and Israel. Agriculture made it possible for the land to support larger communities, then cities.

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 energy via a fireplace. Finally, there must be appropriate brewing vessels for fermentation, such as pottery. In the Fertile Crescent region, pottery is believed to have been invented around 8500 years ago.

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 site called Godin Tepe in present-day Iran. Earlier evidence of a mixed fruit–grain–honey beverage was discovered as residue in pottery from Jiahu in north central China, dating to 9000 years ago. Very recently, 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. 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) before grains were even cultivated as an agricultural product.

**Fermentation and Science**

In addition to its important function at gatherings of political revolution, 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 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 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 (Figure 1.12). 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 noticed 19% nitrogen in dry yeast. Lavoisier considered fermentation to be separation of sugar into two parts, carbon dioxide in an oxidized state and the other, ethanol, in a reduced (deoxygenated) state. 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 published in the 1870s.

In the seventeenth and eighteenth 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 many compounds that occurred in living organisms could not be made in the laboratory from dead matter. In 1828 Friedrich Wöhler (1800–1882) delivered a setback to vitalism 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 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 optical rotation of compounds. Certain compounds, 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 (Figure 1.13). Pasteur regarded fermentation as life without oxygen. He discovered the process of pasteurization 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. Eduard Buchner (1860–1917), while developing methods for an entirely different project, ground several kilograms of brewer’s yeast in a
large mortar with fine quartz powder as an abrasive. He wrapped the result- 
ing 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.

**MUSINGS ON THE HISTORY OF BEER...**

“It is much more productive to study a process in chemical glassware than in 
living cells.”

—Dr. Barth, chemist

“After drinking beer from said process, my neurons say otherwise.”

—Dr. Farber, biologist

Building upon Buchner’s discoveries, Arthur Harden (1865–1940) dis- 
covered that phosphate is a requirement of fermentation. In another key 
experiment, Harden separated yeast lysate 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 
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 revolu-
tion 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 glycolysis and ATP pro-
duction 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 Yakov Oskarovich 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.

To generate new knowledge, scientists must take a systematic and logical approach. Often the observations made, the questions posed, and 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.

Let us use troubleshooting an issue in the brewery as 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.* A hypothesis is a testable statement. It must also be rational and based upon well-established facts. A prediction is a deductive consequence of a hypothesis, typically an “if, then” statement. In this example, the hypothesis is “Fermentation stalled because there were not enough yeast cells.” The prediction is “If too few yeast cells were pitched before fermentation, then the
fermentation will stall.” It is important to consider that the hypothesis may or may not be correct. And there may be additional hypotheses. With appropriate experimentation and analysis, we can decide if the hypothesis is supported or refuted.

4. **Design and run an experiment; record results.** A hypothesis must be testable. 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 other process might have 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. Let us assume 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 are cyclical; it may take 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.

Clearly, if a hypothesis cannot be tested, it cannot be supported by evidence. For an experiment to serve as a test of a hypothesis, an 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. Use of a single variable is critical because if several variables are changed, how will we know which was responsible? To troubleshoot a problem, a brewer might try to fix an issue by changing four conditions. While the problem may have been solved, how will he or she 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 under test, 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 the question of 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 into 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 is a leak, or the yeast was no good. If the zinc chloride flasks differ from the negative control flasks, it 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 critical.

During experimentation scientists gather data, interpret results, and formulate conclusions. What if the experiment was only run once? What is the significance of the experiment? For an experiment to be significant, it must have some type of statistical probability of being correct, and it must be repeatable by others.

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 give more accurate results, 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 1.14 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

![Figure 1.14 Cumulative outcomes of marble draws.](image-url)
large sample, the outcome is subject to error. In this circumstance, 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 through troubleshooting potential problems in the brewery. Case studies are provided in select chapters as a way to critically think about problems that may arise in the brewing process and to propose potential solutions. The ability to troubleshoot, to think scientifically about problems, is one of the greatest skills you can bring to any job.

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 drinker’s expectations.” In this definition, consistency is key as is 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 well defined as fit for use. And finally, beer quality should match the brand values of the company; in other words, the artistic side of brewing also represents quality.

Quality as Freedom from Defect

Beer quality as 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 in place 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 standard of quality still held in high esteem and tradition 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 defect:

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 10ppm, unless specifically reported on the package.
4. American 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 defect. 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 perception 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.

**Perception** Consumers first drink with their eyes. Perception, or the physical quality, 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 this quality. Drinking directly from a bottle or can obscures judgment (which in some cases might be intentional!). Specifically, a number of metrics play a key role 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 study by Carvalho et al. 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 a beautiful thing. Significant effort during production ensures a consistently clear product. Nonetheless, some styles like 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. Anecdotally, hazy IPAs are said to be more flavorful than their clarified counterparts. A recent hypothesis with supporting data from Dr. John Paul Maye has 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. In addition, service temperature and carbonation level 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 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 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 process and also
on style. Stale beer does not have a 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. And of course, beer must be free from microbial contamination of wild yeast and bacteria. Microbial contamination in a packaged product can lead to off-flavors or overcarbonation.

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**BEER QUALITY AND SCHLITZ BEER**

At the start of the twentieth century, the Joseph Schlitz Brewing Company (established in Milwaukee, WI, in 1849) was the largest producer of beer in the United States. Their famous tagline was “The beer that made Milwaukee famous.” But the company suffered great decline in the 1970s. A few years earlier, at the edge of innovation, 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). Clarity issues were resolved by the addition of a clarifier, possibly papain. The resulting foam issue was resolved by adding propylene glycol alginate (PGA). Looking back on it today, it seems as though a business decision was made to cut costs and allow the quality to decline in small increments that the consumers would not notice. This approach is derisively called “salami slicing.” An unexpected interaction between the clarifier and the PGA sometimes resulted in formation of clouds of snowy particles after a few months in the packages. Schlitz management was slow to deal with the issue. Customers found the bits to be unacceptable. Ultimately Schlitz returned to its original recipe, but it was too late. Sales never recovered.

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 product entered the market.
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.

CHECK FOR UNDERSTANDING

1. What is the definition of beer and how does it differ from other alcoholic beverages?

2. Arrange the following units in order of use from start to finish, identify the brewing step in which it is used, and describe the key purpose(s) of the step in beer production.

<table>
<thead>
<tr>
<th>Lauter tun</th>
<th>Fermenter</th>
<th>Centrifuge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate chiller</td>
<td>Mash tun</td>
<td>Mill</td>
</tr>
<tr>
<td>Whirlpool</td>
<td>Boil kettle</td>
<td>Bright tank</td>
</tr>
</tbody>
</table>

3. What are the four major ingredients in beer? At which stage(s) of the brewing process is each added? Discuss all areas for variation.

4. Describe the major process inputs during each step of beer production (i.e. time, temperature, etc.)

5. What are the most important quality goals for packaging operations?

6. Where and when were the origins of beer?

7. What were the three major technological advances that made routine beer brewing possible?

8. What were some of Louis Pasteur’s major contributions to brewing science?
9. What is a *controlled experiment*? Discuss the difference between an independent and a dependent variable.

10. What are some similarities and differences between the scientific method and troubleshooting?

11. Why is it critical to change only one variable at a time during an experiment or while troubleshooting?

12. What government agencies regulate the beer industry in the United States? By law, what metrics must brewers report?

13. Define the Reinheitsgebot and describe its influence on beer quality.

14. Quality is in the eye of the beer holder. What is meant by this statement?

15. What is meant by the phrase “true to type,” and how would you incorporate it into a brewery?

16. You overheard someone at a bar say, “Hazy beer is poor quality beer.” Agree or disagree and explain your position.

17. Describe some of the key changes in flavor during beer staling and comment on their causes.

**CASE STUDY**

A brewery has made the same hefeweizen 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 sensory notes, 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 reached terminal gravity 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?

5. How could the experiment be improved?

**BIBLIOGRAPHY**


