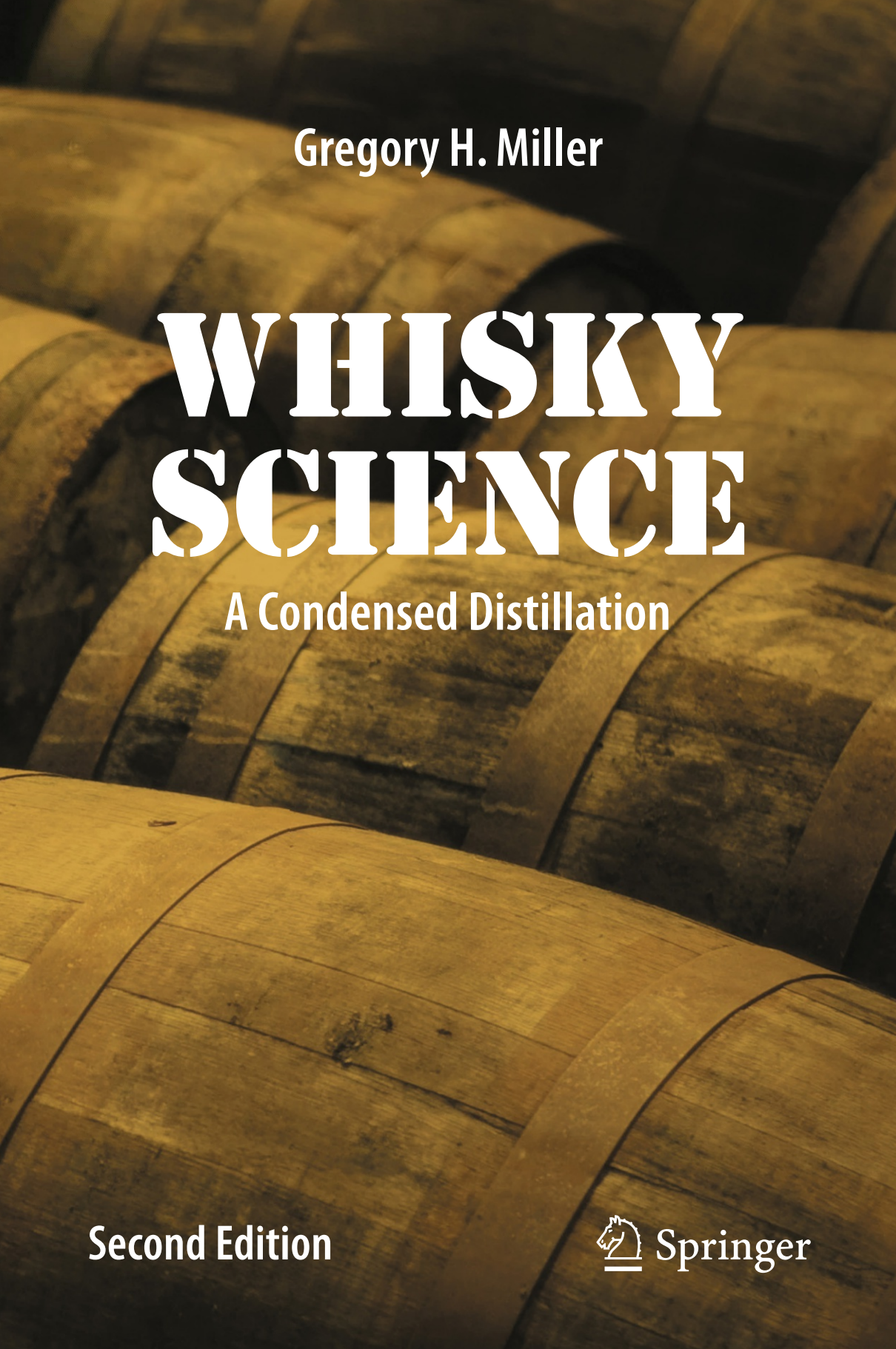
Gregory H. Miller
WHISKY SCIENCE
A Condensed Distillation
Second Edition
Springer

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A Condensed Distillation

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Preface to the Second Edition

Since the first edition appeared, there have been several exciting new research discoveries to share, and a few interesting changes to whisky regulation. Another motivation for this second edition is that there are topics of historic and scientific interest that intentionally weren't covered in the first edition. I needed more time to do them justice, and now I've had some. There are also mistakes needing correction, and some places where the exposition was confusing. Some of these were pointed out by attentive readers, notably whisky scholar Tsung-Chi Yu, and I'm grateful for that helpful feedback. In 2018, Professor Michael Toney and I developed a new lab course, Chemical and Engineering Principles in Whisky and Fuel Alcohol Production, for undergraduates in chemistry and chemical engineering. We've drawn on material from this book for lectures, examples, supplemental reading, and answering student queries. Putting the book through its paces in this way also exposed some opportunities for improvement.

This edition expands on the first in many substantial ways. The history of whisky now embraces Ireland and Canada. The presentation of Maillard chemistry, which touches on several stages of production, is greatly expanded. The interplay between nitrogen in the mash and sulfur in the spirit, and the remedy of sour mash, is clarified. The role of copper is corrected, and the probable mechanisms of its action are given new emphasis. The quantitative analysis of distillation processes now includes triple distillation and hybrid pot-column distillation. Probable mechanisms of oxidation are also described. There is new material in every chapter, supported by over 350 new citations. My favorite addition, although admittedly rather deep in the weeds, is a new analysis of an accessory to Alexander Hamilton's choice, in 1791, for America's first whisky gauging instrument: Dicas' slide rule.

The effort expended in researching a topic often has no relation to the number of words that end up on the page. A great example of this principle is the story of the Honorable Alphonso Taft in relation to a dispute with the Japanese government in 1869, a story which has been repeated many times in the popular whisky literature since it appeared in a 2013 book about bourbon. If the story could be verified with a primary citation, e.g., a court record, or a contemporary newspaper account, it would have been a nice addition to Chap. 1. In the attempt to find corroborating

records, hundreds of hours of effort were expended by dozens of people around the world. I am particularly grateful for the truly heroic sleuthing of Hamilton County Central Services Division Manager Jason Alexander, who led the investigation. The Hamilton County Court records would have been the official repository of Judge Alphonso Taft's story, if the event occurred, and had Cincinnati not burned in 1884. The popular authors were all contacted, but none provided a verifiable reference. Several modern writers have relied on the archives of the Filson Historical Society (Louisville, KY), and Filson researcher Jennie Cole also aided our search and shared numerous scans of historic documents. In the end, we did discover a whisky ruling by Taft, and a whisky dispute with the Japanese government, but neither of these occurred in 1869. They appear together in a newspaper record (Louisville Courier Journal, May 9, 1909, p. 11) unearthed in the Filson's Taylor-Hay archive, but are otherwise distinct. If something of the kind occurred in 1869, we were unable to discover proof of it. Many thanks for the hard work of everyone who contributed to this global effort.

I am grateful for the help of many diverse experts. I learned a lot about warehouse operations from Ian Rich of Springbank. His expertise should have been acknowledged in the first edition and I regret the oversight. Carol Forrester of the International Trade in Goods Section of the Central Statistics Office of Ireland resurrected over 90 years of spirits export data from the archives. Carol Quinn, Archivist for Irish Distillers Pernod Ricard, and David Quinn, Technical Director for Irish Distillers Pernod Ricard, provided data on the past and present operation of their business. Fionnnán O'Connor also shared information on historical and modern Irish distilling, and on Dublin's Dodder bank neighborhood. Sean Nolan, retired Customs & Excise officer, helped to understand the modern role of Customs and Excise in the Irish distilling industry. The late Peter Alan (Tom) Martin generously shared his encyclopedic knowledge of nineteenth century gauging. Alan Park of the Scotch Whisky Association explained the roles of government agencies in relation to the Scotch Whisky product specification. Tillmann Taape helped interpret Hieronymus Brunschwig's *oeuvre*. Professor Kyle Bishop of Columbia University introduced me to the Honorable Noah Sweat, Jr.'s "whiskey speech." Thomas L. Sweat, Jr., Esq. granted permission, on behalf of Judge Sweat's estate, to reprint it. Will Kew, now at the Pacific Northwest National Laboratory, and his colleagues Professors David Clarke and Dušan Uhrín at the University of Edinburgh and Ian Goodall of the Scotch Whisky Research Institute, generously shared some of their high-resolution mass spectrometry data. Professor Alan Wolstenholm of Heriot-Watt University shared an experienced distiller's perspective on Coffey still operation, the industrial use of philosophical bubbles, and some distillery jargon. Dr. Akira Wanikawa of Nikka Whisky Distilling shared thoughts and references on sulfur compounds. Writer Ian Buxton and Professor Paul Hughes of Oregon State University helped fact check a claim on whisky's origins. Ian Buxton also helped me reconstruct the fallout of the Pattison crisis. Meron Kassa of the British Library generously provided copies of Robert Stein's patents. Davis librarian Adam Siegel, and Classics Professor John Rundin helped track down and decipher some medieval distillation sources. Matthew Hofmann and Erik Bennett of Westland Distillery

patiently explained the origin of “American single malt” and the historic usage of this descriptor on labels. Breanna Nussbickel explained Coppersea Distilling’s use of green malt. Will Jamieson, Coby Jamieson, and Dr. Magali Picard of Demptos helped me with the nuances of toasting. Professor Michael Toney continues to teach me chemistry. Thank you all for your invaluable help.

Despite the expert advice received, and my best effort at proofreading, errors and omissions likely remain. Please bring these to my attention so that I can correct the record.

This edition is dedicated to the memory of Wade Hampton Penny, Jr. A long-term president of the North Carolina Scottish Heritage Society, he was proud of his cultural inheritance including the native spirit.

Slàinte

Davis, CA, USA Gregory H. Miller

Preface to the First Edition

This is a book about the science behind whisky: its production, its measurement, and its flavor. The main purpose of this book is to review the current state of whisky science in the open literature. The focus is principally on chemistry, which describes molecular structures and their interactions, and chemical engineering which is concerned with realizing chemical processes on an industrial scale. Biochemistry, the branch of chemistry concerned with living things, helps to understand the role of grains, yeast, bacteria, and oak. Thermodynamics, common to chemistry and chemical engineering, describes the energetics of transformation and the state that substances assume when in equilibrium. This book contains a taste of flavor chemistry and of sensory science, which connect the chemistry of a food or beverage to the flavor and pleasure experienced by a consumer. There is also a dusting of history, a social science.

The main scientific story spans about 125 years, which makes whisky science about as old as modern chemistry. They co-developed, and bursts of whisky discovery accompany developments in analytical chemistry. However, whisky science is distinctly different from most science in an important regard: there is astonishingly little verification. Many relevant studies appear only in conference proceedings, and may not have experienced the standards of peer review enforced by major journals. A surprising number of studies are of a survey nature, involving small numbers of samples that are not sufficiently characterized to enable duplication by other scientists. However, despite the unusual character of this literature as a whole, some of it is of exceptional quality.

There are probably many reasons for this state of affairs. First, whisky scientists often rely on the cooperation of industry, which tends to guard its processes and treat them as proprietary. Second, whisky is a commodity—the businesses making it know how to make it, so research, to the extent it happens at all, is focused principally on economy and quality control, not basic science. Third, financial support for whisky science in the academic community is extremely limited. In America, most university research is publicly funded, and the American public does not tend to fund research on ‘sinful’ products.

The interdisciplinary nature of this subject, and the fact that so much of its literature appears in books and proceedings that can be challenging to obtain, is a motivation for this book. Another motivation is the separation of 'fact' from rumor. It is almost impossible to research whisky using the internet, because the internet is overwhelmed by marketing stories masquerading as historical fact, and by popular wisdom expressed as scientific fact. To deal with this problem, I try to anchor every idea presented here in the literature, with peer reviewed sources used whenever possible. By collecting the key discoveries in one place, I hope this will be a useful resource for future researchers. I also hope that it is interesting and accessible to anybody who likes whisky and chemical engineering. (Doesn't everybody?) The literature offers hints about how processes and materials connect to flavor, so whisky entrepreneurs may find ideas to improve their craft.

The emphasis here is on Scottish and American whiskies. This is in part because the scientific literature is overwhelmingly focused on these products, and in part because of the author's personal interest. This focus may give the mistaken impression that whisky development happened exclusively in these regions. Of course the Irish, Canadian, and Japanese whisky industries are very important, and today whisky innovation is happening on all continents but Antarctica.

This book is not an instruction manual for making whisky. However, some familiarity with the broad outlines is helpful. Before it was highly regulated, it was just a domestic cooking operation:

1. Make a wort. Grind 10 pounds of malted barley. Mix well with 5 gallons of water at about 170 °F such that the mixture has a temperature of 150–155 °F. After 90 minutes, drain the liquid from the solids and set aside. Add 2.5 gallons of water at 180 °F to the solids, stir well, and drain after 20 minutes. The combined liquid is the wort.
2. Make a wash. Cool the wort below 90 °F, pitch 3 tbs dry distiller's yeast, stir well, and store in a cool clean place for 48–72 hours.
3. Make low wines. Distill the wash slowly using an agitator, or a double boiler (aka bain Marie), to prevent scorching of solids. Collect all distillate until the strength becomes negligible (e.g., < 2 °P) at the condenser.
4. Make spirit. Add to the low wines any feints saved from prior distillations. Distill the low wines mixture slowly, paying close attention to the aroma of the distillate. The first few ounces will smell strongly of acetone, and may contain fusel oils washed from the condenser. Set this heads cut aside. When the heads aroma has disappeared, save the condensate as spirit. When the condensate strength starts dropping, in the 120 °P–140 °P range, you will start to detect tail aromas, a bit like the water left over after steaming broccoli. At this point, the remaining condensate is collected with the heads cut to make up feints for future distillations.
5. Mature. The spirit is equivalent to commercial whisky of the early nineteenth century. To make a more modern product, store the spirit in a barrel and wait patiently.

Chapter 1 introduces the history of whisky: the evolution of its character, its methods of production, and its regulation. Next, Chap. 2 explores how the senses of taste and olfaction operate, and what recent studies reveal to be the chemical components of whisky that have the greatest impact on its flavor. The following six chapters examine steps of the production process, as outlined above, to reveal the origin of the chemicals that influence flavor and how process decisions may affect their abundance. In production order, the steps are malting, mashing, fermentation, distillation, and maturation. Chapter 9 describes the spirit matrix: evidence from a variety of experiments that solutions of water and ethanol are not homogeneous at a molecular scale. Rather, there is a structure that depends on alcoholic strength, and that affects the flavor congeners. This structure influences the tasting experience, and it has been suggested that the development of structure is an important part of the maturation process. Chapter 10 concludes with an examination of gauging: the measurement of alcoholic strength and abundance including a critical review of historical methods.

No significance is attached to the spelling. The words "whisky" and "whiskey" are completely equivalent, although there has developed a belief that "whisky" applies to scotch and "whiskey" to bourbon. But, even the law granting special status to the name bourbon didn't care:

> *That it is the sense of Congress that the recognition of bourbon* **whiskey** *as a distinctive product of the United States be brought to the attention of the appropriate agencies of the United States Government toward the end that such agencies will take appropriate action to prohibit the importation into the United States of* **whisky** *designated as "bourbon* **whiskey**."
>
> 78 Stat. 1208, May 4, 1964

For the sake of consistency, I will use "whisky," except in direct quotations where the original spelling will be used.

I am indebted to people in the industry for their help and insights including Will Jamieson, Demptos Napa Cooperage; Dr. John Conner, Scotch Whisky Research Institute; Dr. Harry Riffkin, Tatlock and Thomson Ltd.; sheep herder, farmer, and master blender Nick Charles; Kurt Anderson, Adams Grain; Stephen Beale, KOTQ; Fritz Maytag, founder of Anchor Distilling; Ansley Coale, Craft Distillers; Bryan Davis, Lost Spirits; Christine McCafferty, Archive Manager, Diageo; and Janet Blair, Kerry Hastie, Catherine McDougall, Gordon McDougall, Frank McHardy, Gavin McLachlan, and Robert Scally, of Springbank Distillery.

I am also very grateful for help received from a number of academic colleagues, particularly Professor Emeritus John Piggott, Department of Bioscience and Biotechnology, University of Strathclyde; Professor Emeritus Mike Hale, School of Agriculture and Forest Sciences, University of Wales, Bangor; Professor William Rorabaugh, Department of History, University of Washington; Professor D'Maris Coffman, The Bartlett School of Construction and Project Management, University College London; Mark Norris, Benesch Law; Professor Dennis Pogue, School of Architecture, Planning & Preservation, University of Maryland; Professor Jacob Lahne, Department of Food Science and Technology, Virginia Polytechnic Institute and State University; Professor Charles Frazier, Department of Sustainable

Biomaterials, Virginia Polytechnic Institute and State University; Professor Thomas Collins, Department of Viticulture and Enology, Washington State University; and Dr. Raymond Refausé and Reverend Dr. Adrian Empey, Representative Church Body Library, Dublin.

At the University of California, Davis, I received invaluable help from Librarians Axel Borg, Robert Heyer-Gray, and Adam Siegel; Jason Newborn and all the Interlibrary Loan staff; Enology Professor Roger Boulton; Chemistry Professors Annaliese Franz and Michael Toney; Classics Professor John Rundin; spirits expert William Doering; and the Arochem Society: Professors Walt Harris (now University of Arizona), Charles Hunt, Brian Kolner, Tonya Kuhl, Joe Tupin, and Jerry Woodall. UC Davis students Christopher Ho, Heqing Huang, Nan Luo, Tim Montoya, and Max Oppedahl contributed research, and Naoto Tanaka provided some excellent translations. Anne Bishop made helpful introductions.

In spite of the expert advice received, it is likely that I have made errors and have omitted important works. I apologize if this is the case. Please bring these to my attention so that I can correct the record.

I am especially grateful for the help and support of Carolyn Penny, without whom none of this would have been possible.

Slàinte Mhath!

Davis, CA, USA Gregory H. Miller

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Chapter 1
What Is Whisky?

I shall not today attempt further to define the kinds of material I understand to be embraced within that shorthand description, and perhaps I could never succeed in intelligibly doing so. But I know it when I see it . . .

— Justice Potter Stewart, 1964 (378 US 197)

This chapter presents a brief history of whisky, with a particular emphasis on the events that shaped its flavor and character. This includes technical innovations, but also regulatory policies and the occasional scandal. The historical perspective is relevant to the notion of authenticity: what is whisky today in relation to the past? It also helps to understand the politics behind the whisky science publishing boom around the start of the twentieth century: the birth of whisky science. The studies at the time were significantly tied to the legal disputes over the meaning of the word "whisky" that occurred globally. The scientists involved frequently testified, and wrote opinions seen to support one side, the other, or both.

1.1 The Origins of Whisky

Distillation is an operation that takes advantage of liquid-vapor phase change to modify chemical composition. By this definition, reducing a sauce is a distillation process, and distillation in this broad sense dates from Prometheus' gift of fire. In the fourth century BCE Aristotle wrote "*salt water when it turns into vapour becomes sweet, and the vapour does not form salt water when it condenses again*" (*Meteorologica* 358v16 [20]), showing an understanding of this chemical transformation in the application of distillation to desalinization. The origins of the western tradition are thought to have passed from Greek to Arab societies, who practiced distillation on an industrial scale from the ninth century for the preparation of rose water and essential oils. Distillation to produce alcohol-based medicines occurred in twelfth century Italy [71], and this knowledge circulated throughout Europe in the thirteenth and fourteenth centuries. Taddeo Alderotti, 1233–1303, a physician at the University of Bologna, wrote a short treatise on aqua vitae and

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its medicinal application [110]. He is credited with the invention of the water-cooled serpentine condenser. Previously, condensers were air-cooled, making the manufacture of large quantities of a distillate very expensive.

Many authors, including modern ones, claim that distilled spirits were found to be widely consumed in Ireland at the time of Henry II's invasion (1170–1172). Fairley [65, 66] attributes this belief to the Jesuit martyr Edmund Campion [34]. However, Campion's references to excessive drinking are contemporary (1571) and he does not mention distilled spirits at the time of the attack. Campion's primary source was Henry II's royal clerk Giraldus Cambrensis. In *The Topography of Ireland*, an 1187 account of the Irish people, Cambrensis doesn't mention distilled spirits or beer. He does note that the Irish clergy compensate for long fasting and prayer with "*enormous quantities of wine and other liquors*[1] *in which he indulges more than is becoming*" [234, p. 141]. The wine is said to be abundant, and to be exclusively supplied by foreign commerce. Neither Cambrensis' *The Conquest of Ireland* nor Stanihurst's retelling of it in *De Rebus in Hibernia Gestis* (ca. 1584) [25] offer any support for the idea that distillation occurred in twelfth century Ireland.

However, the *Red book of Ossory* shows that some Irish monks did know about distilling wine in the fourteenth century [89]. By the fifteenth century, this knowledge was available in books outside monastic libraries. Michael Puff von Schrick, a Viennese physician, wrote the broadly circulated book on distillation *Materi von ausgebrannten Wassern* in 1477. Hieronymus Brunschwig wrote *Liber de arte distillandi de simplicibus* (1500) which was translated into Czech and Dutch, and from Dutch to English. The earliest records emphasize the medicinal application of distilled spirits, but increasingly a medicine that could be taken quite liberally:[2]

> It dryeth up the breakyng out of handes, and killeth the fleshe wormes, if you wash your hands therewith. It skoureth all skurfe & skalds from the head, beyng therewith daily washte before meales. Beyng moderately taken, sayth he, it sloeth age, it strengtheneth youth, it helpeth digestion, it cutteth flegme, it abandoneth melancholy, it relisheth the hart, it lighteneth the mynd, it quickeneth the spirites, it cureth the hydropsie, it healeth the strangury, it poũceth the stone, it expelleth grauell, it puffeth awaie all Ventositie, it keepeth and preserveth the hed from whirlyng, the eyes from dazelyng, the tongue from lispyng, the mouth frõ mafflyng, the teeth frõ chatteryng, and the throte from ratling: it keepeth the weasan from stieflyng, the stomache from wambling, the harte from swellyng, the belly

[1] In 1863 translator Thomas Forester chose "and other liquors" for "*variisque potionibus*," which more literally translates to "and various drinks:" distilled spirits are not implied.

[2] In this passage "sayth he" refers to "one Theoricus" and a margin note adds "Theoric. Episc. Hermenensis in Romanula juxta Bononiam." Professor John Rundin hypothesizes that the note refers to Bishop Teodorico Borgognoni, aka Theodoricus Cerviensis or Theodoric of Cervia, 1206–1298, who was a surgeon at the University of Bologna and a contemporary of Alderotti. Indeed, a fourteenth century illuminated Latin manuscript in the University of London's Wellcome Collection contains a section attributed to Theodoricus de Cervia which describes aqua vitae distillation and lists the medical virtues Stanihurst described (Book of learned medical treatises with some additional practical texts, Miscellanea Medica XVIII. MS #544, pp. 84–86). Southey [184, §153] notes that "*The bishop writes of aqua vitæ as if he loved it. No doubt he was full of his subject*."

> from wirtchyng, the guts from rumblyng, the handes from shivering, the sinewes from shrinkyng, the veynes from crumpling, the bones from akyng, the marrow from soakyng.
>
> — Richard Stanihurst, 1577 [188]

Fantastic medical claims such as these were not uncommon.

Aqua vitae (water of life) was the term used to describe alcoholic distillates, and it applied equally to brandies, made from fruits, and to whiskies, made from grains. A frequently cited record gives evidence not only of aqua vitae purchase, but also the specific manufacture of that aqua vitae from malt (*brasii* in Latin): "*Fratri Johanni Cor, per preceptum Compotorum Rotulatoria, ut asserit, de mandato domini regis, ad faciendum aquavite, viii boll. brasii*" as recorded in the Exchequer Rolls, No. 305, in the Privy Purse expenses of Henry VII (1494–5) [59, p. ccxiv]. A boll is an archaic Scottish unit of dry measure, and a Linlithgow boll corresponds to 5 English bushels according to a 1661 standard. However, the meaning of a boll varied in practice even in 1799 [61, App. 38]. The amount of spirit that could be derived from a boll also varied considerably, from 4.5 to 15 gallons at proof in 1799. Depending on the quality of the grain and the skill of Friar Cor, King Henry VII may have commissioned as many as 120 gallons of spirit at proof—a decidedly non-medicinal quantity. Malt whisky, or a close antecedent, was being distilled for beverage use.

In 1555, aqua vitae was of sufficient commercial value that it was granted an exception in a law prohibiting the exportation of foodstuffs in a time of famine:

> Because ane greit part of the liegis of this Realme and uthers strangearis hes thir divers yeiris bygane caryit furth of the samin victuallis and flesche quhairthrow greit derth daylie incressis Thairfoir it is statute and ordanit now that nane of our Soverane Ladyis liegis nor strangearis in tyme cumming cary ony victuallis talloun or flesche furth of this Realme to uther partis except samekill at salbe thair necessare victualling for thair veyage under the pane of escheting of the said victuall or flesche to our Soverane Ladyis use togidder with the rest of all thair gudis movabill to be applyit and inbrocht to our Soverane Ladyis use as escheit Provyding alwayis that it salbe leiffull to the inhabitantis of the Burrowis of Air Irvin Glasgow Dumbertane and uthers our Soverane Ladyis liegis dwelland at the west seyis to have bakin breid browin aill and aquavite to the Ilis to bertour with uther Merchandice And this act to be extendit to the maisters and skipparis of sic veschellis as ressaifis sic victuallis flesche and talloun as to the awnaris of the saidis gudis
>
> — Mary c. 14, June 15, 1555 [142, p. 495]

These records suggest that the distillation of spirit was known to scholars and the clergy from the fourteenth century in the British Isles, and that it was being produced in large quantities in the sixteenth century. However, it was probably not known to the average person as a beverage until the late sixteenth century. Chaucer's *Canterbury tales* (late fourteenth century) do not mention distilled spirits, although alembic distillation in relation to alchemy is mentioned in the Canon's Yeoman's Tale, and in the play Troilus and Criseyde. Shakespeare (late sixteenth century) makes numerous mentions of spirits, mostly medicinal, but some suggestive of beverage use. For example, "*I will rather trust a Fleming with my butter, Parson Hugh the Welshman with my cheese, an Irishman with my aquavitae bottle, or a thief to walk my ambling gelding, than my wife with herself*" (Merry Wives of Windsor).

The procedures for early whisky production are not well known, but John French's *The art of distillation* (1667) gives a recipe which is, in essence, identical to pot-distilled whisky today:

> How to make Aqua Vitæ out of Beer
>
> Take of stale strong-beer, or rather, the grounds thereof, put into a copper still with a worm, distil it gently (or otherwise it will make the head of the Still fly up) and there will come forth a weak Spirit, which is called, low Wine: of which, when thou hast a good quantity, thou maist distil it again of it self, and there will come forth a good Aqua Vitæ. And if thou distillest it two or three times more, thou shalt have as strong a Spirit as out of Wine; and indeed, betwixt which, and the Spirit of Wine, thou shalt perceive none or very little difference.
>
> — John French, 1667 [73]

By the seventeenth century, distillation in well-to-do households was commonplace and the domain of the housewife [117, 123]. Toward the end of the seventeenth century commercial distilling businesses relieved the urban housewife of this chore, and in rural settings distillation increasingly became men's work [123]. Individuals lost the right to distill without obtaining licenses in 1771, Ireland; 1781, Scotland; 1866, America; and 1867, Canada.

Knowledge of the fact that distilled spirits undergo beneficial changes over the time spent in an oak cask surely dates to the first distillation of beverage spirits at scale, likely in the fifteenth century. However, evidence of the marketing differentiation between unaged white spirits and matured aged spirits by producers doesn't appear until 1700–1720 in the cognac trade [50, 231]. Early 1700s France saw great economic instability owing to a large public debt and a period of crop failures. The brandy market was further disrupted by shifting patterns in the international trade of spirits, principally between England and the Netherlands. This economic climate prompted speculation by the best-financed cognac houses: when the market was strong, they favored sale of freshly-made spirit, and when soft they favored holding the brandy back in warehouses where it appreciated in value, though at considerable cost. Records of the Augier cognac house from 1718 onward show price distinctions between newly made cognac and cognacs aged 10 years or more [50]. Comparable records by whisky producers don't appear until the mid nineteenth century.

According to the Oxford English Dictionary, the word "whisky" is dated to the early eighteenth century. Etymologically, the word is thought to be derived from the Gaelic word for water, "uisge" (e.g., [202]). Morewood goes further to say that Latin "aqua vitae," the Irish "usquebaugh," and "whisky" are synonymous [129]; the word "usquebaugh" being a contraction of the Gaelic "uisge beatha," or water of life. Usquebaugh is in fact a cordial, so although the name may be related to whisky the substance is different.

Usquebath, or Irish aqua vitæ

To every gallon of good Aqua composita,[3] put two ounces of chosen liquerice bruised, and cut into small peeces, but first clensed from all his filth, and two ounces of Annis seeds that are cleane & bruised, let them macerate five or sixe daies in a wodden Vessel, stopping the same close, and then draw off as much as will runne cleere, dissolving in that cleare Aqua vitæ five or six spoonfuls of the best Malassoes you can get, Spanish cute[4] if you can get it, is thought better than Malassoes, then put this into another vessel; and after three or foure daies (the more the better) when the liquor hath fined itself, you may use the same: some adde Dates & Raisons of the sun to this receipt; those groundes which remaine you may redistill and make more Aqua composita of them, & of that Aqua composita you may make more Usquebath.

— Sir Hugh Plat, 1602 [151]

Similar recipes are given by French, 1667 [73]; Smith, 1749 [182]; a gentleman, 1793 [74]; Shannon, 1805 [178]; and Boyle, 1808 [28].

1.2 Scotland

In the modern world Scotch whisky is about the only thing left that brings guaranteed and sustained comfort to mankind.

— Lord Robert Boothby, December 14, 1983 [95, p. 233]

Although aqua vitae derived from malt can be traced to the late fifteenth century, until the late eighteenth century Scottish spirituous liquors varied considerably. In 1526 Hector Boece hinted at an usquebaugh-like spiced drink when describing old Scottish manners.

Quhen thay kest thaimself to be mery, thay usit maist aqua vite; nocht maid of costly spicis, bot of sic naturall herbis as grew in thair awin yardis. The common drink that thay usit was aill; and, in time of weir, quhen thay lay in thair tentis, thay usit nocht bot watter.

— Hector Boece, 1526 [26]

In 1703 Martin Martin, a Scot from Bealach on the Isle of Skye, described life on the western isles. He mentions brandy frequently, and (re: the Isle of Lewis):

THEIR plenty of Corn[5] was such as dispos'd the Natives to brew several sorts of Liquors, as common Usquebaugh, another call'd Trestarig, id est Aqua vitæ, three timed distill'd, which is strong and hot; a third sort is four times distill'd, and this by the Natives is call'd Usquebaugh-baul, id est Usquebaugh, which at first taste affects all Members of the Body: two spoonfuls of this last Liquor is sufficient Dose; and if any Man exceed this, it would

[3] Aqua composita is made first by distilling in a pewter alembic one gallon Gascony wine with one dram each of ginger, galangal, cinnamon, nutmeg, grains, anise seeds, fennel seeds, caraway seeds; and one handful each of sage, mint, red roses, thyme, pellitory, rosemary, wild thyme, chamomile, and lavender: usquebaugh was originally made from wine.

[4] "Cute" is wine reduced to 50% by boiling [125].

[5] Corn here means cereal crop: "*This island was reputed very fruitful in corn, until the late years of scarcity and bad Seasons. The Corn sown here is Barley, Oats and Rye; and they have also Flax and Hemp*."

> presently stop his Breath, and endanger his Life. The Trestarig and Usquebaugh-baul, are both made of Oats.
>
> — Martin Martin, 1703 [118]

In 1771, Thomas Pennant (a Welsh zoologist, travel writer, and fellow of the Royal Society) wrote that in the Caithness region much whisky is distilled from barley [147, p. 171]. He also wrote that the highland peasants of the Grampian Hills region drink whisky sweetened with honey [147, p. 109]. In the 1774 edition of his travelogue, he says of the Kintyre peninsula:

> Notwithstanding the quantity of bear[6] raised, there is often a sort of dearth; the inhabitants being mad enough to convert their bread into poison, distilling annually six thousand bolls of grain in to whisky. This seems a modern liquor, for in the old times the distillation was from thyme, mint, and anise, and other fragrant herbs; and ale was much in use with them. The former had the same name with the usquebaugh, or water of life; but by Boethius's account, it was taken with moderation.[7]
>
> — Thomas Pennant, 1774 [148, p. 221]

Evidently the cordial usquebaugh evolved slowly into whisky; the latter being modern in 1774, and with variants of the former still being made at that time. Historical accounts show the use of barley (including bear), but also of oats. A prohibition against distilling wheat or wheat flour, in place from 1757 (30 George II c. 15) through 1773 (13 George III c. 3), suggests that wheat may also have been commonly used.

One record of traditional distillation techniques comes from accounts of highland distilling told soon after it became heavily regulated (e.g., [61]). The general plan is illustrated in Fig. 1.1. Whisky production consists of two distillations. The first distillation takes a fermented wash, low in suspended solids, and produces so-called low wines. The second distillation takes low wines, and foreshots and feints saved from prior second distillations. The distillate is separated in time. The first distillate, called foreshots, and the last distillate, feints, are recycled. The middle cut is whisky. There exist many variations of this simple approach [61, App. 1], differing in the number of cuts made in the second distillation, and the way they are recycled. One practice was to remove the very first part of the distillate, called gall, for use as a salve. Another separated the feints into two cuts: strong feints and weak feints. The former was recycled in the low wine (second) still, the latter in the wash (first) still. A single physical still and worm condenser could serve both purposes though this was not always legal to do.

The first UK excise tax was created by Parliamentary Order effective July 25, 1643, during the Interregnum [70]. It was a broad tax, assessing many necessities: beer, wine, strong waters (at 8d[8] per gallon), fabrics and thread, sugar and spices. A similar law enacted on behalf of royalists by the Scottish Parliament (1644 Charles,

[6] Bear, or bere, is a variety of six-rowed barley.

[7] Boethius is the Latinized name of Hector Boece, p. 5.

[8] £1 = 20s = 240d until 1971, then £1 = 100p.

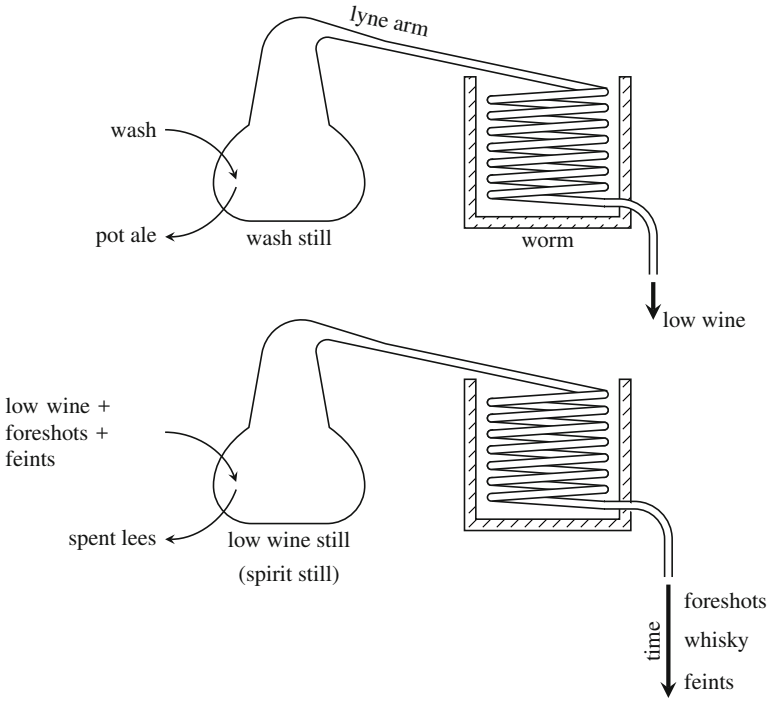

Fig. 1.1 Traditional highland pot whisky production

January 31) imposed a more severe tax of 2s.8d per pint[9] of aqua vitae or strong waters [143]. Over time these taxes expanded to cover more goods, at higher rates, and a Customs and Excise branch of the government was created to enforce them. Beginning in the eighteenth century, excise duties and their associated regulations were a factor that strongly influenced the manufacture and reputation of scotch whisky.

Upon the union of the British and Scottish parliaments in 1707, Scottish distillers became subject to the same excise duty as applied in England: 1d per English gallon of low wines[10,11] (12&13 William III c. 11, 1700). Gaugers recorded wash, low wines, and spirits production, and could assess duty using the assumption that one gallon of wash produced one quarter gallon of low wines, and one gallon low wines produced three fifths gallon of proof spirit (4&5 Anne c. 12, 1705). The duty on low wines was continued for a period of 96 years (5&6 Anne c. 19, 1706), then made

[9] One Scottish pint was 3/8 Imperial gallon.

[10] Six gallons Scots was 17 gallons English.

[11] Statutes from the seventeenth through the nineteenth centuries make reference to "maker of low wines" in a way that suggests this may have been a profession distinct from distiller of spirits.

perpetual (1 George I c. 12, 1714) until withdrawn (27 George III c. 13, §35, 1787). Additional duties upon low wines and proof spirits were assessed through the course of this perpetual tax.

During this period, when excise was based on an assessment of production overseen by excise gaugers, the laws became progressively more severe to assure compliance. Some highlights follow. In 1688 (1 William & Mary c. 24) gaugers could not be refused entry to a distillery, warehouse, or even the distiller's residence, although gaugers were to be accompanied by constables if the inspection was at night. In 1690 (2 William & Mary c. 9) excise officers were instructed to check, from time to time, on the inventory of grains, wash, low wines, and of strong waters, and to charge penalties for suspect discrepancies. Distillers had to give notice of intent to distill or remove spirits if the activity fell outside specified hours.[12] Penalties were imposed if low wines, spirits, or strong waters were concealed from the excise (3&4 William & Mary c. 15). In 1751 distillers were required to submit a written inventory of all stills, coppers, tons, washbacks, casks, or other vessels used for making, laying or keeping any low wines, spirits or strong waters, including casks used for sale. At most two vessels were permitted for the storage of feints (24 George II c. 40, §18). Stills 10 gallons or larger were considered commercial and subject to excise in 1772 (12 George III c. 46). All commercial stills, and all pumps and cocks, had to be provided with locks for the exclusive use of officers of the excise. The locks were to be opened when proper written notice of intent to distill was submitted. Such notice had to be given at least 4 h in advance if during the day, or 12 h in advance if at night. Excise officers had to be present when any locked device was repaired. From 1779 (19 George III c. 50) stills larger than 2 gallons were considered to be commercial. Nobody was allowed entry to a still house or spirits warehouse unless they occupied a tenement valued at £10 per year, assessed in their own name, and unless they paid the parish rates in the parish of their residence.

This unpopular but comparatively stable arrangement began to change when the lowland regions of Scotland began producing large amounts of spirit for export to the English gin market in 1776. Competition with English distillers and the need to generate new revenues for war efforts led to a succession of tax laws which differentiated the highland and lowland regions and had a number of adverse consequences. A relentless churn of new laws followed, each lasting typically 2 years, resulting in what appears to be a quite chaotic, even hostile, business climate. Moss and Hume [131] describe the politics of these laws and the devastating impact they had on the Scottish distilling industry.

In 1781 an exception for distillation for private use was withdrawn: anyone who distilled was a commercial distiller in the eye of the law (21 George III c. 55). Then, in 1784, a distiller was required to obtain a license for his or her still at a cost of 0.5d per gallon of still contents (24 George III sess. 2 c. 41). In the same year a more complicated excise system was instituted (24 George III sess. 2 c. 46) which required more careful monitoring of distilling operations by excise officers.

[12] From September 29 to March 25, 5:00 to 20:00; otherwise 3:00 to 21:00.

These regulations appear to be very heavy handed. There was a duty of 5d per gallon of wort or wash to be used in the creation of spirits for home use (i.e., within Scotland and not for export). The wort had to be gauged by an excise officer, the still had to be filled to 3/4 of its capacity for home use (or 4/5 if intended for export), and the wash had to be worked off within 20 h. Penalties were £200 — over 15 years of a laborer's wages at 10d per day [60] and 6 days per week. The distillate of the wash, called low wines, had to be transferred to the spirit still within 12 h, and run off within 16 h in a still 3/4 full, and the resulting spirit had to be "1 to 10 over proof" by Clarke's hydrometer (see Sect. 10.4.5), subject to £100 fine plus £10 per hour delay. For every 100 gallons of wort used, 20 gallons of 1 to 10 over proof spirits were permitted be made—any excess was subject to seizure.

Section 45 of this 1784 act held that in highland districts of several counties different rules applied (Orkney, Caithness, Sutherland, Ross, Inverness, Argyle, Bute, Stirling, Lanark, Perth, Dunbarton, Aberdeen, Forfar, Kincardine, Banff, Nairn, and Murray), Fig. 1.2. In these regions, where it was assumed that spirit production would be only for personal use, still licenses were significantly more expensive at £1 per gallon still capacity, but the highlanders were not subject to the other duties and fees. Their still size could not exceed 20 gallons, or 30 gallons with a special exemption. Licensees needed a recommendation from their landlords and the justice of the peace. Highland distillers were not permitted to sell spirits outside the highland region, and they were not permitted to import grain from outside this region.

In 1785 the highland laws were redone with a more geographically-specific highland line (25 George III c. 22). In the highland region, stills could be from 30 to 40 gallons including the head. The license fee of £1 per gallon was called out as being a proxy for the amount of malt consumed and of spirit produced. A forty gallon still was permitted to consume up to 250 Linlithgow bolls of barley, and produce up to 1660 gallons of spirit. If production were to exceed this limit, the normal duties on malt and spirits would apply to the excess. The license fee was payable in quarterly installments, but no still under these provisions could be located east of the highland line or within 10 miles of a regularly licensed distillery.

A simplified scheme was adopted in 1786 which made no distinction between the highland and lowland regions (26 George III c. 64). Under this new act, stills were licensed at £1.10s per gallon capacity. Wash stills were required to be 50 gallons capacity or larger, and spirit stills had to be at least 1/4 the volume of the wash still. Only a wash still could be used for wash, and only a spirit still could be used for spirit. A 2s per gallon duty was imposed on spirits for export to England, but there was no cap on production, no duty on wash, and no excise on spirits consumed in Scotland.

The license fee was raised to £3 per gallon in 1788 (28 George III c. 46), then £9 per gallon in 1793 in the lowlands (33 George III c. 61) and £1.10s per gallon in the highlands. A 1795 law doubled the fee to £18 in the lowlands (35 George III c. 17). Distillation was suspended July 17, 1795 (35 George III c. 119) owing to a grain shortage [191], and it recommenced February 1, 1796. The license fee tripled to £54 per gallon still capacity in 1796 (37 George III c. 59).

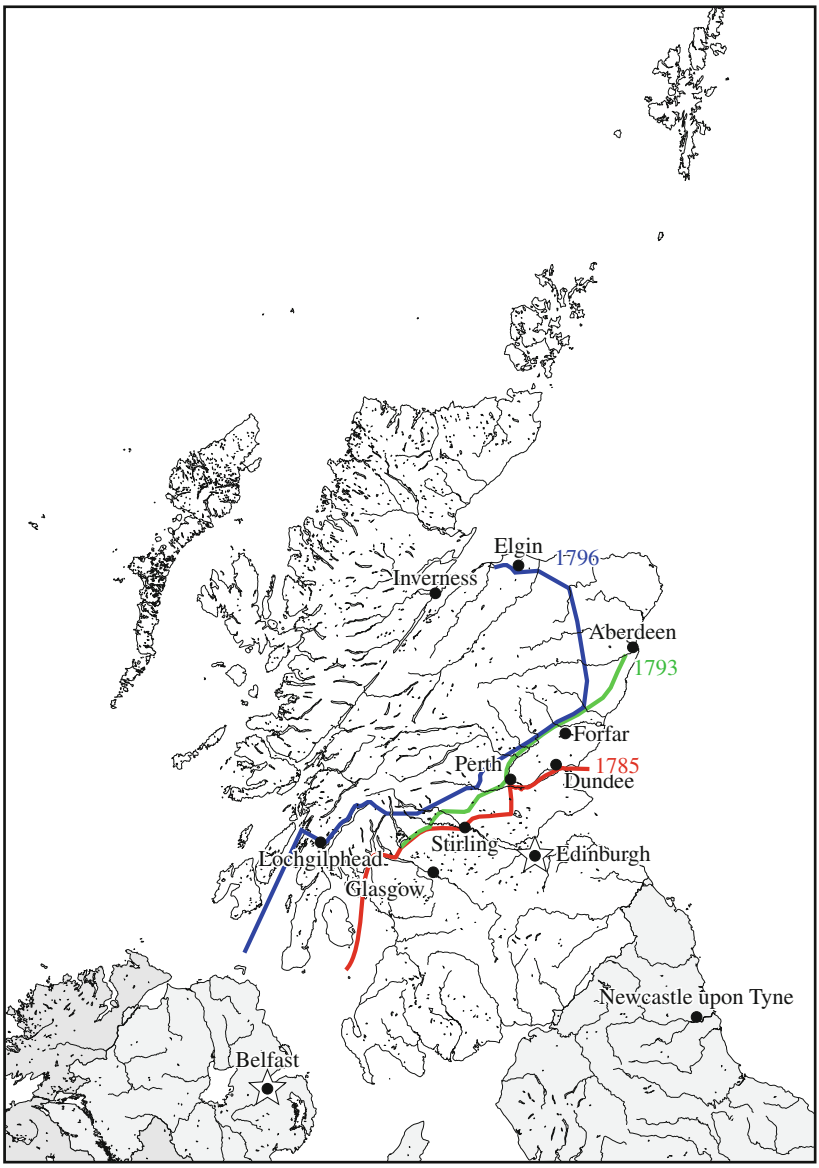

Fig. 1.2 The Highland lines of 1785, 1793, and 1796. Regions to the north and west are the Highlands as regards whisky regulation

The 1793 act (33 George III c. 61) introduced a new highland line which permitted commercial distillation in a large area in the northeast, but excluded a three mile band along the coastline. It reintroduced the "composition duty" by which a 40 gallon highland still license entitled the user to 250 bolls of malt, and 1660 gallons of spirit. Surplus spirit production was fined at 1s per gallon.

A 1796 act (37 George III c. 102) introduced a new system and created yet another highland line, again reducing the extent of the designated highland region. The land between the new highland line and the 1793 one became an intermediate district where a license cost £9 per gallon still capacity. An additional £4 per gallon composition duty for 40 gallon stills permitted an annual consumption of 500 bolls malt. In the intermediate district the license fee was £6.10s per gallon still capacity and £54 in the lowlands. For spirits produced in excess of the amount expected of 500 bolls malt there was a duty of 2s.8d per gallon of spirit in the highlands and 4s.4d per gallon of spirit in the lowlands. In 1798 the duty on surplus production was raised to 3s per gallon in the highlands, and lowland distillers were permitted to use smaller 40 gallon stills (38 George III c. 92).

The strict survey of production accompanying the wash, low wines, and spirit duties was burdensome and unpopular, as it put distillers at the mercy of excise officers, and it led to a number of frauds. The license fee was simpler to implement, but as an indirect measure of whisky production it relied on a critical assumption: that the stills were worked off once a day. A casual or seasonal distiller would be penalized under this system, since their tax burden assumes full time production. Highland distillers largely ignored the law and produced whisky as they had done, then smuggled it to lowland markets where it was welcomed as the traditional wholesome national spirit. Lowland distillers responded differently: by modifying their production methods to work off the stills more frequently. At the Cannon Mills distillery near Edinburgh a 40 gallon still was reportedly worked off once every *8 min*, thereby reducing its effective excise rate by a factor of 180 [61]. According to Muspratt, by 1815 an 80 gallon still could be worked off once every three and a half minutes [133] (Fig. 1.3).[13] Similarly, to avoid the high cost of malt, upon which there was a malt duty, lowland distillers increasingly used unmalted grain in their mash, which increased its productivity but gave it an unpleasant flavor. This had long been a trend of some concern. Adam Smith, the father of modern economics, noted:

> In what are called Malt spirits, it makes commonly but a third part of the materials; the other two-thirds being either raw barley, or one third barley and one third wheat.
>
> — Adam Smith, 1776 [181]

Together these practices allowed the lowland distillers to gain significant economic advantage, especially in the English gin market where the flavor of the spirit prior to rectification mattered little. In the domestic market, the lowland spirit was extremely inexpensive, and this contributed to an intemperance problem despite its disagreeable flavor. Highland whisky was illegal outside the highlands, but greatly prized, commanding as much as three times the price of lowland spirits.

In 1798 the House of Commons commissioned a study of the distilleries in Scotland, headed by Sylvester Douglas, to investigate distillation in relation to excise practices. His committee generated voluminous reports [60, 61] containing

[13] In America, a flat copper still of this character was built for Louisville's Hope Distillery, around 1816. Its singling (low wines) still could process 1500 gallons in 20 min [127].

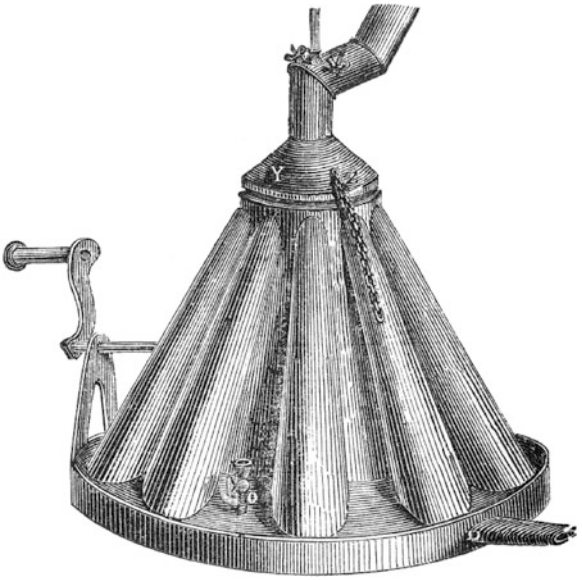

Fig. 1.3 A still designed for rapid distillation [133] by Mr. Millar of the Craigend distillery, Stirling [61, App. M]. The shallow cylindrical base of the apparatus is the body of the still, measuring only $2\frac{1}{2}$ inches in depth at the center. The conical head consists of nine inclined conical channels for vapor flow, surrounding a central gear box chamber. The crank handle drives a rummager. The shaft at the top of the still head drives a fan, which is used to break up foam

testimony from numerous distillers, excise officers, and others, which give an illuminating picture of distillation practices at this time. The committee recognized the cunning of the lowland distillers in evolving their craft to minimize duty, and that the whisky so produced was unwholesome. They recognized that an inequity in the treatment of highland and lowland distillers encouraged the smuggling problem. Significantly, they recognized that the 8 min turnaround time of a lowland still was not a natural limit—increasing financial pressures on the lowland distillers might be met with further ingenuity such that the turnaround time might be reduced to mere seconds. They proposed a specific plan involving a combination of license fees and a survey of spirit production. The former would be an up-front duty on the amount of spirit presumed to be produced in a year, and the latter would serve as a check so that duty could not be avoided by exceedingly rapid distillation. Despite their analysis and recommendations, the licensing system dominated the taxation strategy until 1823 (Table 1.1), and large scale commercial distillation in the highlands was suppressed until that time. (In addition to license fees, in 1800 (39&40 George III c. 73) the wash duty was reintroduced at 2.5d per gallon, and the spirit duty at 6d per gallon, in the lowlands.)

Interestingly, Douglas' commission found several instances where lowland distillers percolated peat smoke through the wash or distillate to give it highland character [60, Whyte, App. 1(A); Maclagan, App. 13].

From 1823 the license fee system was eliminated, the system of survey abandoned in 1784 was reinstituted, and highland distillers were no longer limited to the highlands for purchase of grains or sales of whisky. The excise duty imposed on scotch whisky (Fig. 1.4) is considerable.

Table 1.1 The license fee for distillation in Scotland based on the volume capacity of a still

Year	Act	Fee per gallon	
		Lowland	Highland
1784	24 George III sess. 2 c. 41	0.5d[a]	0.5d[a]
1784	24 George III sess. 2 c. 46	–[a]	£1
1786	26 George III c. 64	£1.10s	£1
1788	28 George III c. 46	£3	£1
1793	33 George III c. 61	£9	£1.10s
1795	35 George III c. 59	£18	£2.10s
1796	37 George III c. 17	£54	£2.10s
1797	37 George III c. 102	£54	£6.10s[b]
1799	39 George III c. 78	£54[a]	£6.10s[a, b]
1800	39&40 George III c. 73	£108[a]	£6.10s[a]
1803	43 George III c. 81	£162[a]	£9.15s[a]
1823	4 George IV c. 94	–[a]	–[a]

[a] Other duties apply
[b] £9 in the intermediate district

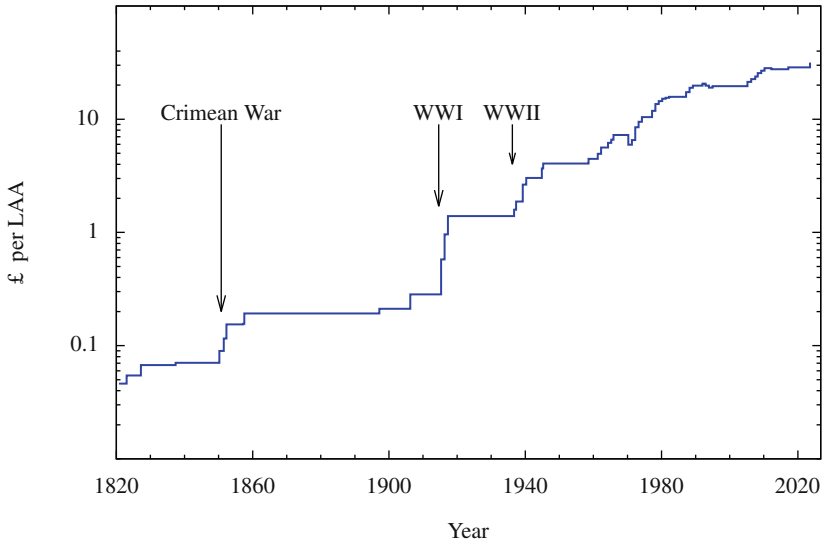

Fig. 1.4 The UK excise tax on scotch whisky since 1823, expressed in pounds sterling per liter absolute alcohol. These numbers are not corrected for inflation. Data sources: 4 George IV c. 94; 6 George IV c. 58; 1 William IV c. 49; 3&4 Victoria c. 17; 16&17 Victoria c. 37; 17&18 Victoria c. 27; 18&19 Victoria c. 22; 23&24 Victoria c. 114; 63&64 Victoria c. 4; 10 Edward VII c. 8; 8&9 George V c. 15; 9&10 George V c. 32; 10&11 George V c. 18; 2&3 George VI c. 109; 3&4 George VI c. 29; 5&6 George VI c. 21; 6&7 George VI c. 18; 11&12 George VI c. 9; 11&12 George VI c. 49; 1964 c. 49; 1965 c. 25; 1967 c. 54; 1968 c. 44; 1969 c. 32; 1972 c. 41; 1973 c. 51; 1974 c. 30; 1975 c. 45; 1976 c. 40; 1977 c. 36; 1979 c. 4; 1980 c. 48; 1981 c. 35; 1982 c. 39; 1983 c. 28; 1984 c. 54; 1985 c. 54; 1990 c. 29; 1991 c. 31; 1992 c. 20; 1995 c. 4; 1996 c. 8; 1997 c. 16; 1997 c. 58; 2008 c. 9; 2009 c. 10; 2010 c. 13; 2012 c. 14; 2013 c. 29; 2015 c. 11; 2017 c. 10; 2023 c. 30; and notices by the Chancellor of the Exchequer acting on authority of 1961 c. 36 §9 in July, 1961 [199] and November, 1968 [200]

> The principle on which Parliament had always acted with respect to the spirit duties was to impose on that article the highest amount of duty which it was possible to levy, without increasing illicit distillation …
>
> — Chancellor of the Exchequer William Ewart Gladstone, 1864 [144, p. 826]

The first highland distillery to be licensed under the new system was Glenlivet in 1824. Its reputation was allegedly established before it became legal when King George IV developed a taste for this highland whisky. Elizabeth Grant Smith, daughter of MP John Peter Grant, wrote in her memoir about the King's visit to Edinburgh in 1822:

> Lord Conyngham, the Chamberlain, was looking everywhere for Glenlivet whisky; the King drank nothing else. It was not to be had out of the Highlands. My father sent word to me – I was the cellarer – to empty my pet bin, where was whisky long in wood, long in uncorked bottles, mild as milk, and the true contraband *goût* in it. Much as I grudged this treasure it made our fortunes afterwards, showing on what trifles great events depend.
>
> — Elizabeth Grant Smith, 1899 [183]

In the period 1776–1823, highland distillers maintained traditional practices using malt, generally employing peat in its preparation, and distilling at a comparatively leisurely pace with copper pot stills as pictured by Sir David Wilkie and Sir Edwin Landseer (Fig. 1.5). The stills were simple, with heights comparable to their diameter. In contrast, lowland distillers typically used some unmalted

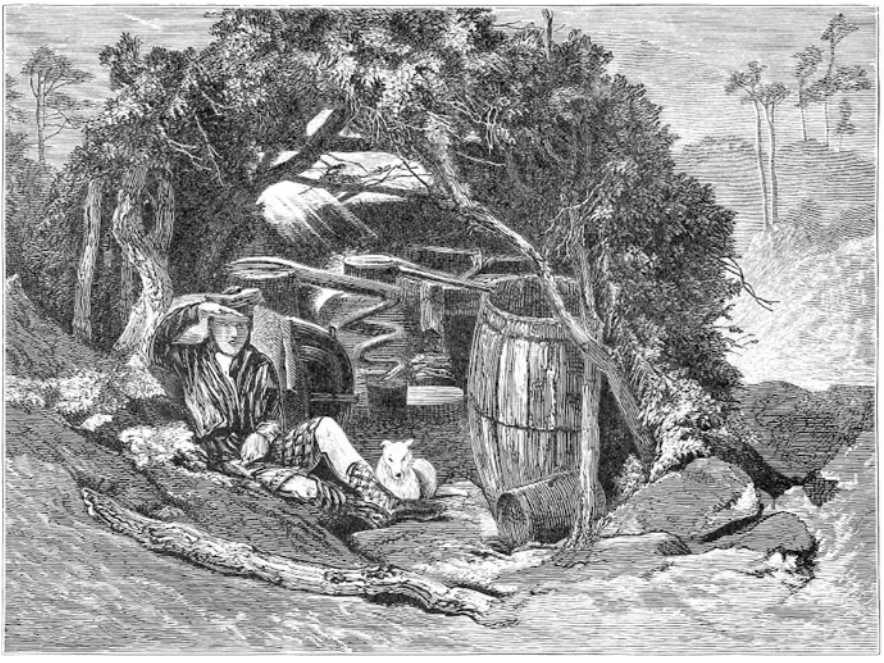

Fig. 1.5 "The Highland Whisky Still" by Sir Edwin Landseer, 1827 [8]

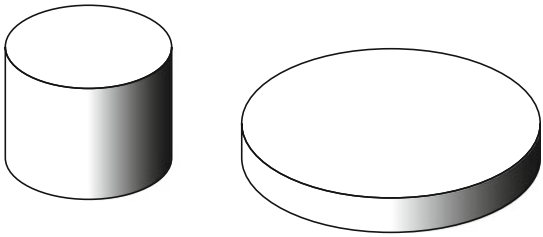

Fig. 1.6 Cylinders of equal volume displaying the aspect ratio difference between traditional pot stills, left, and rapid distillation stills, right, as used at Cannon Mills [61, Levin, App. 5]

grain and employed very rapid distillation—generating spirit targeted more for the rectification market than for direct consumption. From the Douglas commission we know that some lowland pot stills were shallow and broad (Fig. 1.6, cf. Figs. 1.3 and 1.5). The heads were very tall, to prevent ebullition, and hand-operated cranks were employed to drag chains across the heating surface of the still to prevent scorching, and improve heat transfer. These dragged chains, called rousers or rummagers, would be widely used in directly fired stills for the next 200 years. These differences, and the Royal imprimatur, gave highland whiskies a reputational edge that they still enjoy today.

The beginning of the nineteenth century saw a number of significant advances in distilling apparatus. In 1801, Jean-Édouard Adam, a French chemist, patented a still which combined one boiler with several interconnected egg-shaped vessels (Fig. 1.7) [37, 62, 71, 83, 170]. In one mode of operation, the vapor emitted by the boiler passed into the bottom of the first wine-filled egg-shaped chamber where it extracted the alcohol. The vapor exiting the first egg then passed into the second wine-filled egg, and so on. Some eggs could also be configured as dephlegmators, or partial condensers, enabling the production of high-proof alcohol in a single pass. The design is said to have been inspired by a chemistry lab demonstration of Woulfe's bottles [233]. Although not very successful commercially, it inspired a flurry of design innovation. In the succeeding three decades dozens of improved designs were patented throughout Europe [71, 170]. The first truly continuous column was patented by Jean-Baptiste Cellier-Blumenthal in 1818 (brevet no. 2266).

An early continuous design by Robert Stein (Fig. 1.8) was adopted in the Scottish grain whisky industry [129]. This still was first built in 1828 (patent 5721) at the Kirkliston distillery near Edinburgh [224], followed by Cameron Bridge (1830), Yoker (1845), and Glenochil (1846). The Stein still at Cameron Bridge was still in use in 1887 when Alfred Barnard surveyed the distilleries of the United Kingdom [24]. Stein's invention was essentially a modern column still in terms of heat and mass flows, but it was configured horizontally and relied on the action of pneumatic pumps, instead of the force of gravity, to propel the liquid stream. The cylindrical vessel was divided into chambers with hair cloth partitions, which permitted the flow of vapor along the vessel's length while restricting the flow of liquid. Steam entered at one end, and an alcoholic vapor was removed at the other, then condensed. The spirit vapor, and the hot liquid waste stream, were used to preheat the feed in a series