INDUSTRIES OF INDIA

SUGAR

Plant, Crystal, Empire



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S U G A R

Plant, Crystal, Empire

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Reference numbers in square brackets resolve in the companion volume, Sugar: Source Companion.

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PART I - THE SUBSTANCE

Chapter 1 - What sugar is

Open a kitchen cupboard almost anywhere in the world and you will find it: a bag or box of white crystals, so ordinary that nobody looks at it twice. Yet that ordinary substance is a precise chemical compound with a precise name. The crystals are sucrose, and sucrose is one specific molecule, C12H22O11, built by joining two simpler sugars: a unit of glucose and a unit of fructose [S3]. Chemists call it a disaccharide, a double sugar. Everything in this book, the plantations and the factories, the trading houses and the fortunes, the empires and the enslaved, follows from the human effort to extract this one molecule from plants, purify it, and put it into food.

Sucrose is not the only sugar, and the word "sugar" deserves care. In chemistry, sugars are a family of small, sweet, water-soluble carbohydrates. Glucose and fructose occur naturally in fruits and vegetables; fructose and glucose together make honey sweet; milk carries lactose, itself a glucose-galactose pair; cereals carry small amounts of maltose [S29]. Of this whole family, one member dominates commerce to the point of taking the family name. When a shopper says sugar, they mean sucrose, and most commercial sucrose comes from two plants: sugarcane, a tropical grass, and sugar beet, a temperate root. Roughly 80 percent of the sucrose consumed in the world comes from cane, and the remainder from beet [S39]. Other plants give sugar, palms, maple, sorghum, but none has matched that pair at commercial scale; Part III of this book asks why.

The molecule's own behaviour writes the rest of the plot. Sucrose is a non-reducing sugar, its two halves locked together at their reactive ends, leaving the crystal chemically quieter than the reducing sugars; but the bond can be snipped two ways. In the pot and in acidic drinks, acid hydrolysis does it, faster the hotter or more acidic the solution, a reaction called inversion that underlies much of what sucrose does in solution; in the body, an enzyme at the intestinal wall does it instead (Chapter 36) [S-F3, S-F6]. It does not melt cleanly: heated strongly it decomposes into caramel and then char, the pure compound from about 186 degrees Celsius and sooner when impurities are present, which is why caramelisation has a temperature and why burnt sugar is not melted sugar [S-F3]. It dissolves almost beyond belief, about two grams per gram of water at room temperature and more than four at 90 degrees, and a cooling saturated solution becomes a metastable supersaturated one, the physical basis of crystallisation, of the sugar factory's pans, and of every grained sweet in a confectioner's shop [S-F3]. Its solutions rotate polarised light in proportion to concentration, so the industry measures sugar with light, on a scale calibrated in degrees sugar since 1988 [S-F3]. It is the reference standard of sweetness itself, 100 on the relative scale, against fructose at 105 to 125 and glucose at 65 to 75

[S-F3]. And as food it yields about four kilocalories of energy per gram, the fuel value that made it food [S-F3, S-F4].

The white crystals in the cupboard are closer to the plant than most people suspect. To make them, the cane stalk or beet root is broken up and the sucrose is extracted with water. The resulting juice is purified, filtered and concentrated into a syrup, from which the sucrose is crystallised, dried and cooled. What remains behind is a dark syrup, molasses [S29]. Nothing in this sequence changes the molecule. In the standard industry description there is no bleaching step: white sugar is the plant's own sucrose, separated, purified and crystallised, not chemically remade [S29]. Brown sugar is sugar carrying molasses for colour and flavour [S29]. The industry's basic product is thus not an invention but an isolation, and that fact shaped everything about the business: the whole contest was over how much sucrose a plant could be bred to hold, how completely it could be extracted, and how cheaply.

Those crystals reach the kitchen in several working forms. Granulated sugar is the standard. Powdered and icing sugars serve baking and confectionery. Syrups carry sucrose dissolved and ready for beverages, sauces and toppings [S29]. Each form exists because food manufacturers and cooks use sugar for far more than sweetness, a subject Chapter 21 takes up in full: sucrose builds bulk and texture, binds water, feeds fermentation, browns food by caramelising when heated, while the Maillard browning of baked and cooked foods runs on reducing sugars, whether freed by inversion or already present in the other ingredients, and preserves jams and candied fruits by making the water in them unavailable to microbes [S29, S28, S-F3]. Replacing it with a single substitute ingredient is rarely possible without changing the food itself [S29], which is one reason the substance has proved so hard to dislodge from the modern diet, as Part XII examines.

It is worth pausing on how difficult sugar is to make. Salt, humanity's other great white crystal, can be gathered or evaporated from brine with little more than patience and heat. Sugar demands far more: the sucrose molecule sits inside plant tissue, mixed with water, fibre, salts, proteins and other sugars, and coaxing it out pure and crystalline took centuries of accumulated craft [S3]. The historian Ulbe Bosma dates granulated sugar to no more than about 2,500 years ago and the white crystalline product younger still, dates whose foundations Chapter 4 shows are genuinely disputed; what is not disputed is that sugar began its career in Asia as a pure luxury, an ornament of royal banquets and a medicine taken in tiny doses [S3]. Two centuries ago it was still a luxury [S3]. The journey from royal banquet to kitchen cupboard, from rarity to bulk commodity measured in the hundreds of millions of tonnes, is the story this book tells. It begins where the plant began.

Chapter 2 - Sugar in nature

Every green plant is a sugar factory. Photosynthesis turns sunlight, water and air into carbohydrate, and plants move and store that energy as the sugars Chapter 1 introduced. Sweetness in nature is common. What is rare is a plant that stores sucrose densely enough, and accessibly enough, to be worth farming for it. Commercial production today rests on two plants.

The first is sugarcane, a tall perennial grass of the genus Saccharum, kin to maize, wheat, rice and sorghum in the grass family Poaceae [S2b]. Cane is one of the most efficient photosynthesizers in the plant kingdom. It uses the C4 pathway, a turbocharged form of photosynthesis suited to hot, bright climates, and can convert up to about 1 percent of the solar energy falling on a field into biomass [S2b]. The sugar accumulates in the joints of the stalk, the internodes, and a mature stalk is a remarkable package: roughly 12 to 16 percent soluble sugars, 11 to 16 percent fibre, and most of the rest water [S2b]. Under good management a hectare yields 60 to 70 tonnes of cane a year, with the full observed range running from 30 to 180 tonnes [S2b]. In 2020 the world grew about 1.9 billion tonnes of it, two-fifths of that in Brazil, making sugarcane the largest crop on earth by harvested weight [S2b].

The second is sugar beet, a variety of the common beet, Beta vulgaris, that stores its sucrose not in a stalk but in a fat white taproot [S2c]. A modern beet root is about 75 percent water, around 20 percent sugar and 5 percent pulp, with the exact sugar content varying between 12 and 21 percent by variety and growing conditions [S2c]. Where cane rules the tropics and subtropics, beet is the temperate-zone answer, though breeders have pushed experimental beet into tropical and subtropical agriculture too [S2c, S-C33]; Russia and Germany led world production of 294 million tonnes in 2024 [S2c]. The two plants divide most of the world's sugar map between them, cane in the tropics and subtropics, beet in the temperate north, though a few countries, including China and the United States, grow both (Chapter 12), and Part IV follows what the division means for farming.

The beet's sugar content is itself a manufactured fact, and a preview of what breeding can do. When Andreas Marggraf first analysed beets in 1747 he found 1.3 to 1.6 percent sugar [S2c]. The white Silesian beet selected by his student Franz Karl Achard and the Koppy family held perhaps 5 to 6 percent around 1800 [S2c]. Two centuries of selection raised that to around 18 percent in modern varieties [S2c]. Chapter 8 tells that story in full; here it stands as proof that the second sugar plant was, in a real sense, invented.

Why has no third plant joined them at scale? The requirement is brutal: a plant must pack sucrose at high concentration in tissue that yields its juice to simple

crushing or slicing, grow vigorously at farm scale, and propagate reliably. Maple syrup and palm sugar are real commercial products with their own markets, the first at a tiny yield of sugar per tree, the second made across South and Southeast Asia from palms that resist plantation-scale mechanisation; what no third plant has done is enter the bulk sucrose trade this book follows. Fruits and honey are too diffuse or too dear [S29]. Cane and beet won not because sugar is rare in nature, but because concentrated, extractable, farmable sugar is [S2b, S2c].

The final number to hold is what the factories achieve: the refined white sugar of commerce is about 99 percent sucrose [S2b]. From a stalk holding barely an eighth of its weight in sugar, or a root holding a fifth, the industry extracts one of the purest bulk food substances made. How it does that is the mechanical heart of this book, Parts V and VI.

PART II - ORIGINS

Chapter 3 - First contact: New Guinea

Sugar begins in a garden in the western Pacific. On the island of New Guinea and the islands immediately east of the Wallace Line, Papuan peoples took a wild grass called Saccharum robustum and, by selecting and replanting the stalks they liked best, slowly turned it into something new: Saccharum officinarum, the noble cane, a plant with thick, juicy stems that stores sugar in quantities no other wild plant matches [S2]. Genome-wide analysis of 390 cane accessions, published in 2025, confirms the outline: noble cane was domesticated in the New Guinea region from wild S. robustum, its genome a mosaic of different robustum subgroups, and an unknown wild Saccharum, probably East Melanesian, still hides somewhere inside modern varieties [O2]. Cultivation in New Guinea goes back at least 3,000 to 3,500 years, and the crop may have been taken up first as a structural material rather than for sweetness; one review has suggested cultivation possibly 8,000 years ago, but that figure is a suggestion, not a measurement [O1]. The honest limit of the evidence deserves stating: no securely identified cane fragment older than the Middle Islamic period has been found anywhere, so the crop's early history is, in a recent historian's words, difficult to reconstruct genetically and virtually impossible to reconstruct archaeobotanically [O1].

The first cane farmers were probably not after sugar crystals. They grew a useful stalk and chewed it for its sweetness; nobody boiled juice into crystals [O1]. That invention was still thousands of years and thousands of kilometres away. What New Guinea gave the world was the plant itself, already transformed by human choice into a sugar-storing machine.

Cane then travelled with one of the great migration stories of prehistory. The Austronesian peoples, whose descendants would settle from Madagascar to Easter Island, carried useful plants with them in their voyaging canoes, and sugarcane was among the most important of these canoe plants [S2]. A second, independent centre of cane cultivation had grown up in mainland southern China and Taiwan around Saccharum sinense, a primary crop of the early Austronesians from at least 3500 BC; the word for cane is so old in their languages that linguists reconstruct it in Proto-Austronesian as *tebuh [S2]. As the sweeter noble cane from New Guinea spread westward into Island Southeast Asia it met and hybridised with local canes, including the wild Saccharum spontaneum, and over time replaced S. sinense across much of its range [S2]. Voyagers carried cane eastward into Polynesia and Micronesia by around 1500 BC, and traders carried it westward and northward to China and India by around 1000 BC [S2]. Every one of these dates is an evidence-based estimate that further archaeology may revise, and the book treats them that way.

One detail in this westward journey matters for everything that follows. In India, the introduced noble canes crossed with local canes of the S. barberi group, producing hardy hybrids adapted to the northern plains [S2]. Those Indian hybrids would matter enormously thousands of years later, when breeders at Coimbatore and Java used them to rebuild the world's cane varieties (Chapter 7). The plant's earliest journeys already contained the genetic raw material of the modern industry.

Did anyone in the Pacific make true sugar from this cane? Some scholars have speculated that Polynesians may have produced granulated sugar by a simple process; direct evidence is thin, from cultures without writing, and archaeology has so far supplied no sugar-making remains to settle it, so the possibility stays open and unproven [S2]. The first credible written evidence of crystallisation appears elsewhere, in ancient India, and that is where the next chapter goes.

Chapter 4 - The invention of crystallization

A stalk of cane is mostly water and fibre. Chewed or pressed, it gives a sweet juice that spoils quickly and travels badly. For most of cane's long history with humans, that juice was all there was: a perishable pleasure to be consumed near the field. The invention that turned a garden grass into a world commodity was the discovery that the juice could be boiled down, and that something entirely new would emerge from the boiling: hard, translucent crystals that kept for months, travelled across oceans, and carried sweetness further than any fruit or honey ever had.

The first credible written evidence for this invention points to ancient India [S2]. The Sanskrit word for the product, sharkara, originally meaning grit or gravel, is the ancestor of the word "sugar" in nearly every language on earth, passing through Prakrit and Persian into Greek, Latin and Arabic before reaching the modern European tongues [O5, O3]. The crystals themselves were called khanda, which survives, via Persian qand, as "candy" [O5, O3]. Precisely when Indians first mastered crystallisation is a genuine scholarly dispute, and this book reports the dispute rather than picking a winner. One widely used history of sugar, reading the Sanskrit literature as presented in a 1964 study of sugar-making in ancient India, allows references to crystalline sugar as early as the late sixth century BC. A specialist in medieval Islamic sugar argues from the Greco-Roman evidence for a late development, sometime after the first century AD. A third authority calls the dating of the Sanskrit texts contestable and puts the earliest clear evidence in the third century AD or later. The most recent review of the question calls it difficult, if not impossible, to resolve [O1]. The historian Ulbe Bosma's summary of the arc sits inside that range: granulated sugar is no more than about 2,500 years old [S3].

What the early process involved, in its essentials, is known: crushing the cane for its juice, boiling the juice to drive off water, and letting the concentrated syrup stand so that crystals formed and could be separated from the remaining dark liquid [S2]. Every refinement since, the vacuum pans and centrifuges of Part V, improves on this same three-step idea. The process was valuable enough to draw imperial attention. Chinese documents record the imperial interest directly. In 647 CE the Tang emperor Taizong sent envoys to Magadha for sugar-making skills, and the official history records the result: "Taizong commanded Yangzhou people to offer sugarcanes, and let craftsmen follow the Indian ways to make sugar, the product of which was much better even than Indian sugar in both color and taste." A monastic biography adds that the ambassador Wang Xuance "called up sugar-makers" at the Mahabodhi Monastery, enlisting two craftsmen and eight monks, with production supervised at Yuezhou; Buddhist monks travelling between the two civilisations

carried the knowledge both ways, and China established its first cane plantations in the seventh century [O6, S2].

To the ancient Mediterranean world, Indian sugar was a curiosity in lumps. The physician Dioscorides, around 65 AD, described saccharon as "a kind of honey which solidifies in India, and in Arabia Felix; and is found upon canes, in its substance resembling salt, and crunched by the teeth as salt is," recommending it, mixed with water, for the belly and stomach. Pliny the Elder, a few years later, called it a honey collected in reeds, white and gum-like, brittle, in pieces no bigger than a hazelnut, used only in medicine; Galen, a century on, still listed it among the stomachics. These texts, quoted here from the great 1903 Anglo-Indian glossary that collected them, describe a substance their authors had met rarely, at apothecary prices: Rome knew cane sugar as an imported medicinal solid, not as a food crop or a common sweetener [O5, O1]. One long philological argument held that the ancients' saccharon was not sugar at all but tabasheer, a siliceous concretion from bamboo; the 1903 glossary disputes that at length - tabasheer is slightly bitter, a hydrate of silica, and "could never have been called honey" - and recent scholarship reads the texts as sugar while stressing how marginal a substance it was [O5, O1]. A modern linguistic paper can still write that sugar was unknown to the Greeks and Romans; the texts say otherwise, and the persistence of that oversimplification is itself a small lesson in how sugar's history gets told [O7].

When the craft reached Persia is disputed by a century and a half: the Encyclopaedia Iranica puts sugar-making in Sasanian Persia around 460 CE, and Chinese sources long credited the Sasanians with inventing the refining of syrup into hard sugar, while the most recent archaeological-historical synthesis puts cane growing in Sasanian Iran in the early seventh century, probably no earlier [O3, O1]. The scale it could reach there survived in ruins: in 1826 the British officer Robert Mignan walked the banks of the Karoon River in Khuzestan and found vast heaps of flat grinding stones, four to six feet across, the remains of mills that had once crushed cane for a medieval sugar industry important enough to leave miles of ruins, and forgotten enough that its discoverer had to guess what the stones were for [S3]. From Persia and the Arab medieval expansion, sugar and the craft of making it moved west toward the Mediterranean. Chapter 5 follows it.

Chapter 5 - Sugar travels west

From India, sugar moved with empire and trade into the Islamic world. Cane and its craft reached Persia around the time of the Arab expansion - the exact century is disputed, as Chapter 4 noted - and spread across the caliphate: to Mesopotamia, Egypt, North Africa and Andalusia [O3, O1]. The medieval sources document a real industry, not a sprinkling. The geographer al-Jahiz, who died in 868, counted the Ahwaz district of Khuzestan - a province whose very name means land of the sugar cane - among the great producers of sugar; a century later the geographer Ibn Hawqal, surveying the region, reported that in Iraq "there was no village without sugar cane" [O4, O3]. Egypt's first clear reference is a mid-eighth-century papyrus, and by Mamluk times the scale was industrial: one sultan's domain at Mallawi alone carried 2,500 feddans of cane, and in 1337-38 the crown seized 14,000 qintars of raw sugar from a single estate's supervisors; the town of Qift housed forty refineries [O4]. The traveller Ibn Battuta described Mallawi's eleven cane-pressing factories as so open that beggars walked in with hot bread, dipped it in the boiling juice pots, and walked out with the bread steeped in syrup [O4].

The Levant's boom came later and is documented factory by factory. In the tenth century the geographer al-Muqaddasi still called sugar a product of Palestine "rare in other countries"; by the early thirteenth, Yaqut named it the Jordan Valley's principal product, and dozens of sugar factories were founded across the coastal plain and the valley as European demand rose - a mid-century crusade chronicle treats sugar as unfamiliar, while William of Tyre, writing in the 1180s, calls Tyrian sugar "a most precious product," carried "to the most remote countries" [O1]. The boom fed a graded international market: a Florentine merchant handbook of about 1343 lists sugars by origin and grade, mucchera reserved for the Sultan, caffettino, bambillonia from Cairo, musciatto, dommaschino from Damascus, chandi, and powdered sugars of Cyprus, Rhodes and Alexandria [O5]. Then the Levant's industry faded as fast as it rose: by the mid-fifteenth century its villages had turned to cotton, sesame and cereals, and Ottoman tax registers that show two Jordan Valley villages lucrative enough in the late fourteenth century for Sultan Barquq to endow their revenues to his Cairo mosque show neither producing any sugar by 1538 [O1]. "Wherever they went, the medieval Arabs brought with them sugar, the product and the technology of its production," one historian of the crop summarises; the newer scholarship adds the correction that introduction, establishment and boom were often centuries apart in the same region [S2, O1]. Medieval Egypt grew a sugar industry served by merchant houses like the Karimis, and Cyprus and Sicily became important production centres [S3, S2b].

Europe met sugar first as medicine and marvel. The Greeks and Romans had known it as an Indian curiosity in apothecary lumps (Chapter 4). Returning Crusaders encountered caravans carrying what they called "sweet salt," and early in the twelfth century the Republic of Venice acquired villages near Tyre and set up estates to produce sugar for export home [S2]. For centuries sugar supplemented honey, until then Europe's main sweetener, at prices only the rich could pay [S2]. By the fifteenth century Venice stood as Europe's chief sugar refining and distribution centre, with Genoa known for candied fruit and Venetian confectioners producing sugar sculptures for princely banquets: at a feast in Tours in 1457 the final course was a heraldic menagerie of lions, stags and monkeys sculpted in sugar, each holding the arms of the Hungarian king [S2].

The decisive step west was geographic: out of the Mediterranean, into the Atlantic. Prince Henry the Navigator introduced cane to Madeira in 1425, and the Spanish carried it to the Canary Islands as they subdued them [S2]. The islands suited the crop, and Madeira's rise was meteoric and measured: little sugar exported in 1452, 280 tons in 1472, Europe's leading producer by the 1490s, displacing Sicily and above all Cyprus, then a peak of nearly 2,500 tons in 1506 - followed by a contraction of some 90 percent by 1530 [O9]. One historian argues the island collapsed under the exhaustion of the forests that fuelled its boilers; that is his thesis, and Chapter 37 examines it, but the chronology itself is documented, and the template simply moved on - to Sao Tome by the 1540s, Pernambuco by the 1570s, Bahia by the 1620s, Barbados by the 1670s [O9]. Here, on Atlantic islands worked increasingly by enslaved Africans, Europeans assembled the arrangement the Atlantic world would run for centuries: plantation cane, mills, and export sugar for the European market [S2]. The template was built, tested and profitable. It needed only a larger stage, and Columbus opened the way to one in 1492.

Through this whole long westward journey, one fact holds: sugar remained an Asian product at world scale. The historian Ulbe Bosma's survey of the crop's global history finds that most of the world's sugar was produced in Asia until the 1870s [S3]. The Atlantic system that was about to rise would not displace Asia's sugar so much as outgrow it, building production on a scale, and with a coerced labour force, beyond anything the Mediterranean industry had known. Chapter 6 follows that rise, and Part XI confronts its human cost.

Chapter 6 - Sugar comes to the Americas

A luxury stowed aboard

When Columbus's second expedition left the Canary Islands in the late months of 1493, cane cuttings went aboard at La Gomera along with the rest of the fleet's provisions, and they were planted on Hispaniola sometime after landfall [S2, EC-8]. The detail is repeated in nearly every history of the Caribbean, and historians have just as often missed what is strange about it. Cane was a demanding luxury crop. It wanted water, fuel, capital equipment, and a reliable route to consumers who could pay for sweetness. A raw colony on the far side of the Atlantic, still imagined by its sponsors as a trading factory rather than a settlement, had none of these [EC-8].

That the plant survived at all owed little to planning. The colony's first economy was gold, mined with indigenous labour under the encomienda grants that Governor Ovando stretched, against his instructions, into a general system of land and labour allocation. Around the mining towns grew a small class of encomenderos who controlled land and Indian workers and sold food to the miners. It was in their world, in the rich plain of La Vega Real, that cane first found a foothold [EC-8].

In 1503, at Concepción de La Vega, a local encomendero named Pedro de Atienza and the town's fort warden Miguel Ballester built the island's first cane-processing works - a modest mill making melazas, low-grade molasses, in partnership. Others in the Vega followed. But these early mills were crude affairs, apparently modeled on thirteenth-century Egyptian designs, and the industry could not grow past them. The mountain wall of the Cibao cut the Vega off from the south coast, where the capital, the consumers, and the port were. A good mill could produce more sugar than local markets could absorb, and no one with capital saw reason to build one [EC-8].

The Hispaniola workshop, 1503-1575

What changed the calculation was the exhaustion of gold. By 1516, after a decade of production, the mines' yields were declining, and the small group of men who had grown rich on gold, encomienda tribute, and colonial offices needed somewhere to put their wealth. Sugar prices were rising. In that year a settler named Vellosa found no difficulty raising capital: he entered partnership with Cristobal and Francisco de Tapia, respectively inspector of the royal foundries and warden of the fortress of Santo Domingo, to build the island's first true sugar mill [EC-8].

The Tapia-Vellosa mill embodied the decisive technology. Its design derived from one developed at Palermo in 1449 by Pietro Speciale: two vertical rollers pressed together in a frame, turned through gearing by a water wheel or a horse-drawn sweep. The water-powered version, called an ingenio locally, was the most powerful and could produce on average about 125 tonnes of sugar a year [EC-8]. It was also industrial equipment of a wholly new order of expense. The minimum cost of a good mill rarely fell below fifteen thousand gold ducats - far beyond the reach of the small landowners of the day. From the beginning in the Americas, sugar selected for men with access to capital, office, and credit, and the mill, not the field, set the scale of the enterprise [EC-8].

The Spanish crown quickly recognized an industry worth promoting. The Jeronimo friars, governing in 1518-19, diverted local revenues into modest loans of five hundred pesos to prospective planters and personally promoted four- and five-man partnerships in three port towns. Once Charles I had been impressed by their reports, he ordered his judge Rodrigo de Figueroa to lend from the royal treasury, ultimately about six thousand gold pesos, to anyone willing to build an ingenio, with whatever privileges would encourage them; a further loan followed in 1533 [EC-8]. It is an early and clear instance of a pattern this book will meet again: sugar's capital demands pulled the state in as financier long before they pulled it in as taxer.

The crown's money worked. The Tapia-Vellosa mill prospered, and its profits, like those of other successful mills, were ploughed into daughter mills. By the end of the 1530s Hispaniola had reached a fairly stable total of thirty-four mills, only four or five of them the small horse-drawn trapiches, and the count held steady until the industry collapsed suddenly in the mid-1570s [EC-8]. By then Hispaniola had already been overtaken, but its half-century as the American workshop of sugar had fixed the template the rest of the hemisphere would copy: a costly central works, a dependent ring of canefields, a workforce increasingly recruited from Africa, and a product aimed from the start at Europe.

Two corrections belong here, because the early numbers are often inflated in the telling. The documented record supports neither the claim that several thousand mills were built in the Americas before 1550 nor the claim of hundreds on any single island by 1540. Hispaniola, the pioneer, had thirty-four mills at the end of the 1530s; the whole of Brazil a decade later counted sixty-five [EC-8, E14]. The early industry was small. Its significance was the machine and the method, not the volume.

Brazil builds the first sugar economy

Portugal came to cane in its new possession almost as early as Spain. Sugar was introduced around 1530 on the island of Itamaraca, off Pernambuco, by the colonial administrator Pero Capico, and the hereditary captaincies gave the crop its footing [E14]. The Madeiran and Sao Tome experience described in Chapter 5 supplied the know-how; the supply of enslaved Africans, first across from Guinea and then in a swelling transatlantic stream, supplied the labour that indigenous workers, dying and resisting, could not be made to provide in the numbers the mills required [E14, O9, EC-2].

The growth was fast by any contemporary standard. In 1549 Pernambuco already had thirty sugar mills, Bahia eighteen, and Sao Vicente two. Half a century later the captaincies together counted about 256 engenhos [E14]. The surviving fiscal and clerical surveys let us see the engine in detail: in Bahia, Gabriel Soares de Sousa's careful description of 1587 found thirty-six engenhos in operation and more building, and a report of 1589 put the captaincy at fifty mills - by a wide margin the densest concentration of industrial plant anywhere in the Americas [EC-9]. By the early seventeenth century Pernambuco was the largest and richest sugar-producing region in the world, and its planter aristocracy dazzled visitors; Father Fernao Cardim thought its tables and beds finer than Lisbon's and concluded that "in Pernambuco, one finds more vanity than in Lisbon" [E14].

The Brazilian engenho perfected what Hispaniola had sketched: a landed, capitalized, slave-worked estate whose owner, the senhor de engenho, stood at the centre of a web of dependent cane farmers, creditors, and carriers, producing a single commodity for a single distant market [E14, EC-9]. The forest-fuel logic that J. W. Moore has traced in the Atlantic islands ran here too, on a continental scale: each zone's cane frontier consumed its accessible timber and moved on, and the centre of production shifted in succession from Sao Tome in the 1540s to Pernambuco in the 1570s, Bahia in the 1620s, and ultimately Barbados in the 1670s [O9]. How that succession worked, and what it did to the people inside it, belongs to Chapters 34 and 35. What matters to the story of transplantation is the direction: for a century, the American sugar economy was Portuguese, and Brazil was sugar.

The Dutch bridge and the Barbados revolution

The vector that carried sugar from Brazil to the Caribbean was war. The Dutch, excluded from Iberian trade by the union of the Spanish and Portuguese crowns and fighting for their independence, struck at Brazil: they seized Salvador in 1624, were expelled the following year, returned in 1627, and from 1630 held Recife and Pernambuco itself [EC-9, E1]. For a quarter of a century Dutch

Brazil was a going sugar concern, and Dutch merchants, refiners, and financiers learned the business from the inside. When the Portuguese drove them out in 1654, the diaspora of planters, technicians, and capital scattered across the Caribbean and the Guianas - and the English and French islands were ready buyers [E1].

The mechanism of transfer can be dated almost to the year. In 1640 James Drax, a Barbados planter, obtained from Dutch Brazil a triple-roller mill and copper cauldrons and applied them to cane on an island that had until then grown cotton, tobacco, and indigo with indentured English servants. The switch worked spectacularly. Within a generation Barbados had become the richest European colony in the Caribbean, a position it held for roughly a century, and the "sugar revolution" - the rapid conversion of small islands into monocrop plantation economies worked by enslaved Africans - had its archetype [E1]. By 1680 the median Barbados plantation held about sixty enslaved people [E1]. The cane frontier's own logic followed: Barbados's accessible timber burned through in decades, windmills supplemented muscle power, and the search for fresh caneland pushed English settlement to Jamaica and the Leewards and the French to their own islands [E1, O9].

The demand side moved just as fast. By 1660 England's sugar imports exceeded those of all other colonial products combined [E15]. English consumption per head rose from about a pound a year around 1670 to some twenty-five pounds by the 1770s, and for a century and a half down to 1820 cane sugar from the Caribbean was, in Kenneth Morgan's summary, the most valuable single import in British trade [E15]. Sugar was no longer a luxury stowed aboard a fleet. It was becoming a staple of European diet, and the American plantation was its machine.

The eighteenth-century peak

From the 1740s the industry's two giants were Jamaica and French Saint-Domingue [E1]. Saint-Domingue, the western third of old Hispaniola - the same island where the American industry had begun - became by the middle of the century the most productive sugar colony ever seen. Its planters imported on the order of thirty thousand enslaved Africans a year in the years before the French Revolution, and its output exceeded that of all the British West Indies combined [E15]. French engineering money went into irrigation works - reservoirs, dams, aqueducts - that pushed cane onto drier plains, an early sign that the ceiling on the plantation system would be set as much by water and fuel as by land [E1].

The wealth flowing back along the chain was no longer confined to planters. A careful quantification of the eighteenth-century British sugar trade finds the Caribbean-to-Britain sugar commodity chain generating value added of roughly

one percent of British GDP early in the century, rising to around four percent by about 1800 - with the bulk of the gain accruing not in the colony but in Britain's tertiary sector: shipping, insurance, finance, refining, and distribution [E46]. What that wealth did to and for British capitalism is a contested question reserved for Chapter 35. The point here is the shape the American industry had reached at its apex: a slave-worked plantation frontier whose product, by the later eighteenth century, sat near the centre of the Atlantic economy.

Revolution and reorganization

The peak broke on the same island where it had begun. In 1791 the enslaved of Saint-Domingue rose, and after thirteen years of war Haiti emerged in 1804 as the first state founded by a successful slave revolution [S2]. The greatest sugar colony in history was gone, and the vacancy reorganized the map. The mechanisms of that reorganization were threefold: new frontiers, old refuges, and steam.

Cuba took the crown. The British occupation of Havana in 1762 had already opened the island to slave imports and trade on a new scale; production climbed from about 14,000 tonnes in 1790 to 34,000 tonnes in 1805 as the Saint-Domingue collapse opened the market, and free trade from 1818 accelerated the rise - 55,000 tonnes by 1820, roughly a million tonnes by 1895, by which time Cuba was the world's leading raw-sugar producer with about fifteen percent of world output [E10]. By the 1860s, on Moreno Fraginals's figures, Cuba produced more than a quarter of the world's sugar and a third of its cane sugar [E11]. The Cuban takeoff was the first industrial one: steam mills, rail networks to feed them, and eventually the great centrales - machinery belongs to Part VI, but the competitive logic belongs here, because it rewrote what a sugar economy was. Cane agriculture stayed in the field; the factory became the commanding unit.

Louisiana shows the same reorganization at the edge of a continental republic. Cane had failed there repeatedly since the early 1700s; Jesuits had grown it in their gardens in the 1750s. The catalyst was again Saint-Domingue: refugee sugarmakers arriving after 1791 carried the crystallizing expertise Louisiana had lacked, and in 1795 Etienne de Bore, on the plantation that is now Audubon Park, made the granulation work at scale - some 100,000 pounds of sugar, rising to over 550,000 pounds shipped by 1797, with seventy-five sugar mills operating by 1801 [E18]. Antebellum Louisiana came to produce ninety-five percent of the sugar grown in the American South, selling chiefly raw sugar at the daily auction on the New Orleans levee, financed by factors and planters' banks and protected, in boom-and-bust cycles, by federal tariffs it lobbied for from the start [E18]. Louisiana also hosted a decisive piece of the industry's modernization: the first steam cane mill in 1822 and, in the 1830s, Norbert

Rillieux's multiple-effect evaporation, the most important nineteenth-century advance in sugar manufacture [E18].

By the 1890s the transplantation begun in 1493 had run its American course. Sugar had moved from a Canary Islands cutting to the island workshop of Hispaniola, to the continental engenhos of Brazil, to the revolutionary monocultures of Barbados and its imitators, to the eighteenth-century apex of Saint-Domingue, and finally to the industrial plantations of Cuba and Louisiana - each move a step up in scale, and each resting on the same foundation of enslaved African labour until emancipation forced the industry to reorganize again. The next part of this book turns to the people who did that work.

PART III - THE PLANTS

Chapter 7 - Sugarcane: the plant and its breeding

Sugarcane is a grass that behaves like a factory input, and it was made that way. Left wild, its ancestor Saccharum robustum is a lean, runnering cane of New Guinea with little juice [S39]. The cultivated noble cane, Saccharum officinarum, stands 2 to 7 metres tall with stout, jointed, fibrous stalks, and every stalk is a bundle of sugar-rich internodes ready to be cut, crushed and replanted [S2b]. The genus Saccharum sits in the tribe Andropogoneae of the grass family, alongside sorghum and maize, and traditionally comprises six species; the two that matter for the modern crop are the noble cane and the wild S. spontaneum, a tough, thin-stalked species whose chromosome count runs from 40 to 128 and whose gifts are disease resistance, vigour and the willingness to grow where noble cane sulks [S-C2, S-C6]. Who first turned robustum into officinarum is lost, but the where is not: the New Guinea region, as the genome evidence of Chapter 3 confirms [O2]. Even the name travels: Saccharum is thought to descend, by a long linguistic road, from the Sanskrit sharkara [S-C2].

The engine inside the stalk is C4 photosynthesis, and it explains where sugar comes from. Most temperate plants fix carbon dioxide directly through the enzyme rubisco, which in hot, bright conditions wastes a share of its work grabbing oxygen instead, a leak called photorespiration. Cane, like maize and sorghum, runs a two-stage system: a first set of cells captures carbon dioxide into a four-carbon compound and shuttles it into deep-bundle cells, where rubisco works bathed in pre-concentrated gas, wasting almost nothing [S-C2]. The payoff is a growth rate few crops match in full tropical sun, and the reason a hectare of well-watered cane can out-produce nearly anything else a farmer can plant. The C4 machinery is also why cane belongs to the heat: its advantage shrinks in cool, dim climates, which is precisely the niche the other sugar plant fills.

A stand of cane is harvested not by seed but by pieces of itself: cuttings carrying at least one bud go into the ground, and after each harvest the plant sends up new stalks, called ratoons, giving two to ten successive harvests before declining yields force replanting [S2b]. The scale of this vegetative system is easy to miss. Australia alone, a mid-ranking producer, raises an estimated 880 million of these stalk cuttings, called setts or billets, every year [S-C2]. The material is perishable in its own right: a cut sett stays viable only about three to four weeks, which is why seed cane is mostly grown on the farm that will plant it, a crop within the crop [S-C2]. Brazil adds an industrial answer to the same problem: commercial micro-propagation, tissue-cultured plantlets that supply disease-free planting material at scale [S-C2]. Clonal propagation has a deeper consequence for the whole industry: every plant of a variety is genetically the

same individual, multiplied. A cane variety is not a breeding line in the grain farmer's sense but a single genotype, captured once and copied millions of times, which is why variety names carry so much weight in this book.

The crop's calendar is written in temperature and light, and Chapter 9 gives the working numbers. One calendar fact shapes breeding itself: cane flowers in response to shortening daylength, and a flowering stalk progressively spends its stored sucrose on reproduction, so varieties are bred and managed not to flower, keeping the stalk a warehouse rather than a nursery [S-C1].

Beneath the field habits lies one of the most complex genomes in agriculture. Sugarcane is highly polyploid: modern cultivars carry on the order of a hundred or more chromosomes, counts varying by cultivar, where most crops carry a neat paired set, the result of repeated hybridisation between Saccharum species [S-C5, S-C6]. All the sugarcane species can interbreed, and every major commercial variety is a complex hybrid of several of them [S2b]. That complexity is the industry's inheritance from a century of breeding, and it began with a problem.

By the late nineteenth century the world's plantations ran on a handful of noble canes, thick-stalked and sweet but vulnerable: slow to mature in subtropical margins, prone to disease, and difficult to propagate by seed [S39]. The crisis that forced the fix had a name: sereh disease, which devastated Java's cane in the early 1880s and pushed the colonial industry to found research stations in 1885, 1886 and 1887, among the world's earliest commodity research stations; the East Java station, the Proefstation Oost Java at Pasuruan, founded 9 July 1887, became the famous one, and 'sereh' entered the world vocabulary of cane disease from Java [S-C23]. The station's path ran through the seed itself: Dr Soltwedel's 1887 work on cane seed and germination underpinned breeding programs internationally for decades, and by 1897 the station's collection already held 121 imported varieties, including a Red Fiji cane tested against sereh [S-C23]. Its wonder cane was POJ 2878, resistant to sereh and mosaic, and a parent of most commercial varieties worldwide [S-C23]. The fix, worked out in Java and in India, was to cross the noble canes with their hardier wild relatives and then breed the offspring back to noble cane again and again, a process the breeders called nobilization: recurrent backcrossing that kept the wild cane's toughness while restoring the noble cane's sugar [S39]. Java's breeding station produced the POJ varieties, named for the Proefstation Oost Java, which spread across the cane world [S2].

Nobilization worked almost too well, and the mechanics explain both the triumph and the fragility. Modern canes descend from three or four species, but remarkably little wild germplasm actually entered them: the Java form of S. spontaneum enters most pedigrees through a single natural hybrid called

Kassoer - in one breeding-history review's framing, through effectively one sampled gamete [S-C24]. Unreduced chromosome transmission from the noble-cane female in the first generations accelerated the return to high-sugar types, which is why the whole arc from first cross to commercial variety could run in a working lifetime [S-C6, S-C7]. The crop the twentieth century inherited was thus rebuilt from a genetic bottleneck so narrow that much of the world's cane shares close cousins for ancestors.

The other great centre was Coimbatore, in southern India, where the British established the Sugarcane Breeding Station in 1912 under the botanist Charles A. Barber [S39]. His deputy and successor, T. S. Venkatraman, spent three decades there crossing S. officinarum with the wild S. spontaneum that grew locally and with Indian S. barberi canes [S39]. The station's first release, Co 205 in 1918, yielded more than 50 percent above the native varieties [S-C3, S-C4]; a foundation biography records that it replaced them within six to eight years [S39]. Later Coimbatore varieties travelled the world: Co 281 became a leading cane in Louisiana, Cuba and South Africa, and Co 419 was hailed as the wonder cane for the tropics, serving for four decades [S39]. The institute that grew from that station reports that most present-day varieties worldwide carry Coimbatore canes in their genealogy; it has released more than 2,900 Co varieties and keeps the world's largest sugarcane germplasm collection at Kannur [S-C3, S-C4]. Venkatraman, knighted in 1942 and later awarded the Padma Bhushan, had shown that wide crosses, crosses between different species and even different genera, could work where conventional wisdom said they would fail [S39]. Virtually every cane variety grown today carries ancestry from these programs [S39].

The genome papers have now caught up with the breeders. Sugarcane is a C4 grass, built for fast carbon fixation in hot sun, and its genome matches its hybrid history: about 10 gigabases of DNA, some three times the human genome, roughly 70 to 80 percent noble cane, 10 to 20 percent wild spontaneum, the rest recombined [S-C5, S-C6, S-C2]. In 2018 researchers produced the first reference genome, a monoploid path through the cultivar R570, 382 megabases carrying 25,316 gene models; in March 2024 the full polyploid assembly arrived, 8.72 gigabases across about twelve chromosome copies, with 194,593 coding sequences, resolving among other things the Bru1 brown-rust resistance locus [S-C6, S-C7]. The 2024 paper carries a pointed historical footnote: the variety POJ2878, a product of Java's breeding station, is both the maternal and paternal grandparent of R570, a measure of how narrow the modern crop's ancestry is [S-C7]. Its sobering conclusion is that sugar-yield gains from conventional breeding have plateaued; until that paper, sugarcane was the last major crop without a reference-quality genome [S-C7]. Gene editing is the proposed answer, and Chapter 40 takes it up [S-C5].

The breeding chapter of this story is not finished. Modern programs still work to widen the narrow base, crossing cane with relatives like Miscanthus and Erianthus, and Part XII returns to what gene editing may change [S39, S2b].

Chapter 8 - Sugar beet: the temperate answer

The second sugar plant was born from chemistry, not agriculture, and its parent was a Prussian academy. In 1747 Andreas Sigismund Marggraf of the Berlin Academy of Sciences isolated sugar from beetroots and proved the critical point: the sugar in the beet was identical to the sugar in cane [S2c]. He found it at concentrations of only 1.3 to 1.6 percent, far too lean for commerce, and his discovery sat on the shelf of science for a generation [S2c]. The idea itself was older still: the French agronomist Olivier de Serres had boiled red beetroot into a sweet syrup as early as 1575, but crystallised cane sugar tasted better and was already available, so nothing came of it [S2c].

The plant Marggraf worked on was no obscure species. Sugar beet is the Altissima cultivar group of Beta vulgaris, the same species that gives the kitchen red beetroot, Swiss chard and the mangold of the cattle shed, and its closest wild relative is the sea beet, Beta vulgaris subspecies maritima, a salt-tolerant scrambler of Atlantic and Mediterranean coasts that breeders still return to when the crop needs new resistance genes [S-C9]. In nature it is a biennial: the first year builds a rosette of leaves and a swollen storage root, and only after surviving the cold of winter, a physiological trigger called vernalization, does the plant bolt, flower, set seed and die [S-C11]. The entire sugar industry lives inside the first half of that life cycle, harvesting the root at the moment of maximum stored sugar, before any second season begins. And the crop carries its life cycle's main risk into every spring: a young beet that meets enough cold can be fooled into bolting in its first year, running to seed instead of filling its root, which is why bolting resistance and sowing date are twin obsessions of beet breeding and beet farming [S-C9, S-C11].

Marggraf's student Franz Karl Achard spent his career turning the laboratory result into a crop. Beginning in 1786 at Kaulsdorf near Berlin, he evaluated twenty-three beet varieties for sugar content, selected a local strain from Halberstadt, and opened the world's first beet sugar factory at Cunern in Silesia in 1801, under the patronage of King Frederick William III of Prussia [S2c, S2]. The white Silesian beet that resulted from Achard's selection, refined further by Moritz Baron von Koppy and his son, held perhaps 5 to 6 percent sucrose around 1800, and it is the progenitor of every sugar beet grown today [S2c]. The Cunern factory itself was never profitable and was destroyed in the Napoleonic wars [S2]. The crop, not the factory, was the achievement.

It was war that made beet an industry. The slave uprising in Saint-Domingue, the most profitable cane producer in the New World, destroyed the plantations that had supplied France [S6]. Then, from October 1806, Napoleon's continental blockade and Britain's counter-blockade cut France off from colonial sugar

entirely, and the price climbed until cane sugar all but disappeared from French markets [S6]. France moved methodically: in 1809 a commission of the Institute of France, including the chemists Chaptal and Fourcroy, tested and confirmed Achard's method; in 1810 the first French beet sugar factory opened at Lille under Louis Crespel-Dellisse; and on 25 April 1811 Napoleon's decree put the state behind the crop, setting aside land for beet and founding six experimental schools [S6]. Later wartime measures went further, and one widely cited account records an 1813 ban on cane sugar imports with 32,000 hectares ordered into beet [S2]. French entrepreneurs built the industry on this foundation: Benjamin Delessert achieved practical beet sugar production at Passy, aided by charcoal purification, and Jean-Baptiste Queruel industrialised his methods [S2, S-M12]. The early efforts were fragile, but they were the prerequisite for the industry's real growth in the 1830s and 1840s [S6]. When peace restored cane sugar competition, the beet industry survived on chemistry, tariffs and steady breeding. By 1840 about 5 percent of the world's sugar came from beet; by 1880 the share had passed half [S2c, S2].

The beet's rise created an industry structure cane never had. Beet grew on ordinary temperate farms, in rotation with grain and pulses, and the factories that sliced and diffused the roots ran as seasonal campaigns around the clock while the harvest came in [S2c]. The crop demanded deep, well-prepared soil and heavy labour until the late twentieth century; Chapter 10 tells that mechanisation story [S2c].

The breeding arc completes the story Chapter 2 began: it made sugar beet as much a manufactured object as any machine in Part VI [S2c]. Two centuries of selection layered improvement upon improvement: first sucrose itself, then the shape and chemistry of the root for factory work, then resistance to bolting, then the seed technology that made mechanised farming possible, then resistance to the diseases that each new intensity of cultivation invited [S-C9]. A recent review puts modern beets at 15 to 20 percent sucrose depending on region [S-C33]. And like cane, its modern success carries a dependency: beet's defenders note that it let temperate countries grow their own sugar, but the crop's advance was built on protection as much as on agronomy, a political thread Part XI examines [S3].

Between Achard and the gene engineers stands one of the great human stories of crop science. Beet "seed" is naturally a multigerm fruit, a dried ball containing several embryos, so sown beets come up in clusters and must be thinned; a monogerm fruit gives one plant, and with it the possibility of precisely spaced, mechanised fields. In 1934 Soviet workers screened more than 22 million seed bushes and found 109 monogerm plants; the character was recessive, and the discovery was credited to a researcher named Kolomiets [S-C28]. The work

passed through remarkable hands. Viacheslav and Helen Savitsky, leading Kiev beet geneticists trained under Vavilov, fled west with the retreating German army in 1943, lost their seed stocks, and reached the United States in 1947 through the intervention of the Nobel laureate H. J. Muller, hired by a consortium of western American beet companies [S-C28]. Asked to find monogerm beets again, Viacheslav walked a four-acre field in Salem, Oregon, some 300,000 plants, and found five; two proved true, and one of them, SLC 101, became the foundation line [S-C29]. The second half of the trick was sterility, deliberately used. Cytoplasmic male sterility, just then discovered in beet, leaves a plant unable to shed fertile pollen; a field of male-sterile mothers planted beside a chosen pollinator can set only cross-pollinated seed, which is exactly what a breeder needs to produce uniform first-generation hybrids by the tonne. The Savitskys built monogerm male-sterile lines, practical hybrid beet varieties became possible, and USDA distributed the material to breeders across America and Europe [S-C29]. Monogermy plus male sterility plus hybrid vigour is the genetic stack under every modern beet field.

The twentieth century's last beet revolution was genetic engineering, and its geography is telling. Glyphosate-tolerant beet was ready by 2000, held back by consumer concerns, then deregulated in the United States in 2005; commercial planting reached about 60 percent of the American crop within two seasons and about 95 percent by the 2009/10 crop, survived a court ruling that briefly revoked approval in 2010, and was fully re-deregulated in 2012 [S-C17]. It remains approved commercially only in the United States and Canada, and the refined sugar it yields is molecularly identical to any other, which is precisely why the fight was about farming rather than food [S-C17]. Europe, where the crop was invented, grows none of it.

PART IV - FARMING

Chapter 9 - Growing cane

Cane is a demanding crop with simple rules. It wants heat, sun and water: a tropical or subtropical climate, no severe frost, and plentiful moisture for a continuous stretch of more than six or seven months a year, from rain or irrigation [S2b]. Most of the world's cane grows between 22 degrees north and 22 degrees south of the equator, with outliers to about 33 degrees where warm currents or sheltered coasts allow, and it climbs to 1,600 metres near the equator in Colombia, Ecuador and Peru [S2b]. It is less fussy about soil than about weather, growing on everything from fertile mollisols to heavy cracking clays, but it feeds heavily: cane consumes about 9 percent of the world's potash fertilizer production [S2b]. Well-watered desert agriculture can out-yield the humid tropics; Egypt's irrigated fields are among the highest-yielding cane regions on earth [S2b].

A cane field is not sown, it is assembled. Farmers plant stalk sections, each carrying at least one bud, by hand or by billet-planting machines that open the soil, drop the billets and close it again [S2b]. The densities are those of a standing construction: rows usually 1.1 to 1.4 metres apart (wider, around 1.5, in Australia), and 21,000 to 35,000 setts to the hectare [S-C1, S-C2]. The plant that rises will be harvested, and then it will regrow: the ratoon crops of Chapter 7 let a single planting carry two to ten harvests, the count depending on local practice. Mechanised farms chasing maximum yield replant after two or three ratoons; traditional smallholdings, as on Reunion, may ratoon for ten years [S2b]. Every ratoon yields a little less than the crop before it, so the replanting decision is an economic calculation repeated on every farm on earth, and Chapter 12 takes up the arithmetic.

The ratoon is also a physiological bargain worth understanding. A regrowth crop springs from an established root system, so it races ahead of a new planting: one comparison from irrigated Indian conditions has a ratoon maturing in about 295 days against 482 for plant cane, and the energy accounts reported in the review literature imply roughly 2.3 times less production energy per tonne of ratoon cane, an approximate figure from the review literature [S-C8]. Ratoons cover about half the cane area in the tropics and somewhat less in the subtropics, and how long a farm can keep them going depends on soil care, harvest damage and, above all, disease [S-C8].

The crop's working numbers, as FAO's reference agronomy records them, are guidance rather than universal constants, varying with climate and variety. The growing period runs from 9 months where frost limits it to 24 in Hawaii, typically 15 or 16; sprouting wants soil at 32 to 38 degrees Celsius, growth a mean of 22 to 30, and ripening a cooler, drier finish [S-C1]. Water demand is

1,500 to 2,500 millimetres over the season, and the craft lies in its timing: light, frequent water at establishment, the deepest need during stem elongation, and a deliberate drying-off before harvest that forces the plant to bank sucrose instead of growing [S-C1]. The Indian breeding institute's field experience puts a finer point on the same curve: the formative phase, roughly days 60 to 150, is the critical water window, and drought striking there can cut a season's yield by up to half [S-C4]. Furrow irrigation still dominates where water is applied; sprinklers spread where land and capital allow, and drip, used at scale in Hawaii's cane, delivers the tightest control of all [S-C1].

Feeding follows the same logic of early plenty and late restraint. Cane is moderately salt-sensitive, which matters on irrigated land with poor drainage. A 100-tonne crop takes roughly 100 to 200 kilograms of nitrogen, 20 to 90 of phosphorus and 125 to 160 of potassium per hectare, and the final phase wants low soil nitrogen, because a cane plant still growing at harvest is a cane plant not storing sugar [S-C1]. Where the pressure to cut inputs meets good agronomy, use falls: Australian nitrogen application dropped from 206 kilograms per hectare on the 1997 crop to 164 by 2008 without the industry losing its yield position [S-C2]. Weed control is overwhelmingly chemical, herbicides making up about 90 percent of pesticide use on Australian cane farms; chemical ripeners exist, ethephon is registered, but growers reach for them little, preferring to let the season do the work [S-C2].

Disease is the standing threat to all of this, and the roster is worth knowing by name. Ratoon stunting disease, a bacterium with no obvious external symptom, steals yield invisibly, betrayed only by red-brown dots at the nodes inside a sliced stalk; smut replaces stalks with dark whiplike shoots and shortens ratoon life; Fiji leaf gall, the disease that once wrecked Fiji's industry, remains a biosecurity border story where it has been kept out [S-C25]. The viruses travel by aphid, yellow leaf syndrome among them, a syndrome tied to both a virus and a phytoplasma; mosaic spreads by the cane knife as well [S-C4]. The fungi bring red rot, the disease every breeding program tests its candidate varieties against [S-C22, S-C4]. The pests run from stalk borers, eldana in Africa, Sesamia and Chilo across the tropics, to aphids, armyworms, nematodes and longhorn beetles, each with its own geography and its own resistant-variety story [S-C25]. Overseas loss figures run to 40 percent for downy mildew and higher for the phytoplasma diseases in susceptible varieties, numbers quoted from biosecurity assessments, not universal experience [S-C22]. Every breeding program in Chapter 7 is, in the end, a standing army against this list.

Harvest is where cane farming shows its two faces: fire and the cane knife on one side, the chopper harvester on the other, with the fire retreating as machines

advance. Chapter 11 takes up the harvest itself; what matters here is what the choice does to the field.

Mechanisation, though, imposes its own discipline. Cut cane is perishable: it begins losing sugar the moment it is severed, and machine damage accelerates the loss, so mechanically harvested cane must reach the mill fast [S2b]. This single fact organises the geography of the whole industry. Mills must sit within hauling distance of fields; harvest, transport and crushing run as one continuous campaign against decay; and the mill's clock, not the farmer's, sets the pace of the district. Chapter 11 takes up the harvest campaign itself, and Part V begins where the cane arrives at the factory gate.

Chapter 10 - Growing beet

Beet farming is cane farming's mirror image: an annual crop in a temperate rotation, planted in spring and lifted in autumn, instead of a perennial grass harvested from regrowth [S2c]. The sugar beet wants deep, well-prepared soil rich in nutrients and humus, level and well-drained; it grows best between 15 and 21 degrees Celsius through its growing months, needs about 460 mm of rain or its irrigation equivalent, and rewards long, mild sunshine rather than fierce heat, which is why the crop thrives at high latitudes and in high valleys from Michigan to Idaho [S2c]. It exhausts soil quickly, so rotation is not optional: the classic pattern puts beets on a field one year in three, with peas, beans or grain between [S2c].

Where cane is planted as stalk pieces, beet grows from seed, and tiny seed at that: one kilogram contains about 100,000 seeds and plants more than a hectare [S2c]. The season that follows runs through four distinct acts, and each carries its own risk [S-C11]. First comes establishment, the nervous phase: emergence is slow, two or three new leaves a week in cold soils, and a stand can be lost to weather, pests or a smeared seedbed before it ever gets going. The central hazard is the bolting of Chapter 8: a spell of cold long enough to register as winter in the plant's biennial programming can trigger the premature flower stalk that ruins the root, so sowing date and bolting-resistant varieties are chosen together [S-C9, S-C11]. Then, from about the six-true-leaf stage, the canopy races until the rows close over, reaching a leaf area index around 3 and intercepting 80 to 90 percent of the season's light; every day gained or lost in that race is sugar made or sugar foregone [S-C11]. Third comes the storage phase, when the root swells and sucrose pours in at its fastest daily rate. Finally the leaves senesce while the root holds its sugar, and the crop stands ready for the lifters [S-C11].

The rhythm of the crop year ends with the campaign. In most of the northern hemisphere the harvest begins with the first hard frost, which stops photosynthesis and further root growth; the roots are lifted over weeks or months and rushed to factories that run twenty-four hours a day for the duration, about five months in Britain [S2c]. Beets that cannot go straight to the factory are piled into clamps, ventilated heaps protected by straw, because a beet that freezes and thaws produces complex carbohydrates that play havoc with factory processing; Chapter 11 follows what that storage costs and how it is managed [S2c].

The crop's labour history is a mechanisation story in miniature. Until the late twentieth century, beet demanded dense planting and two or three passes of hand thinning with hoes during the season, then a harvest of pulling, knocking

and topping with a short-handled beet hook, row by row, by hand [S2c]. Today mechanical sowing, herbicide weed control and harvesters that top, lift, clean and load six rows at a pass have displaced nearly all of that [S2c]. The gang labour that once defined the crop survives only in the phrase the industry still uses for its frantic harvest-processing season: the campaign [S2c].

The modern beet crop's deepest battles are biological, and two stories define them. The first is rhizomania, "root madness," first observed in northern Italy in 1952 and only explained in 1973, when Japanese researchers identified the cause, a virus carried by a soil organism whose resting spores contaminate a field effectively forever [S-C16]. Sugar-yield losses of 50 to 60 percent were common, with up to 80 percent documented; quarantine failed, no pesticide reaches the vector, and the crop was saved by breeding: the resistance gene Rz1, found by American researchers in the 1980s, later joined by genes from wild sea beet; resistance-breaking virus variants have already evolved, so the race continues [S-C16]. The second is virus yellows, a complex of aphid-borne viruses that can take half a crop. Britain's 2020 epidemic is the documented case study: neonicotinoid seed treatments had suppressed the disease for 26 years while cutting soil insecticide use by up to 90 percent; the EU ban reached beet in 2019, a mild winter followed, and 2020 brought the largest aphid migration since national trapping began in 1965, infecting 38 percent of the national crop and costing an estimated quarter of the yield, after which several European countries re-authorized the treatments under emergency rules [S-C15]. Writing in 2021, the trapping record's keepers noted that the five highest early-season aphid migrations in the record had all come in its last seven years, a climate signal hanging over the whole debate [S-C15]. Beneath the headline diseases runs a soil fauna ledger of its own: free-living nematodes causing Docking disorder in sandy soils, and a pest complex of millipedes, symphylids and springtails nibbling at seedlings [S-C15]. And the chemical cupboard itself is thinning: EU growers now work with 53 plant-protection active substances at the European level, down steadily under regulatory pressure, which is why each loss of a tool like the neonics lands so hard [S-C18]. A third disease redrew the map in America: cercospora leaf spot, the most destructive foliar disease of the central High Plains, drove Nebraska's beet production westward as early as the 1920s and still takes up to 40 percent of a crop where it takes hold [S-C30]. Older and worse was curly top, among the first viral diseases ever recognised in plants: it crippled the young western American industry, closing factories and nearly bankrupting Spreckels Sugar in 1926; in 1934, 85 percent of planted American beet acreage was abandoned to it [S-C31]. The rescue came from USDA breeder Eubanks Carsner's mass selection: the first resistant commercial variety, US 1, in 1933, and by 1941, 97 percent of acreage was harvested at nearly triple the yield; because Europe had no curly top, the fight also created an

American beet seed industry where seed had always been imported [S-C31]. It was the committee behind that fight, the Curly Top Resistance Breeding Committee, that would later hire the Savitskys of Chapter 8 [S-C29, S-C31].

The crop is also pushing into cane's climate. Breeding and agronomy for tropical sugar beet, short-duration varieties grown through warm winters, promise a beet crop of five or six months against cane's year and more, at lower water demand; tropical trials have recorded roots of half a kilogram to two kilograms at 15 to 20 percent sucrose, and the idea is on trial from Pakistan and India to Bolivia, Sudan, Kenya and Malawi [S-C33]. Whether beet can really take lowland tropical acres from cane is an open question, but the experiment reverses two centuries of geography: the temperate answer testing itself in the tropics.

The contrast with cane now shows its economic outline. Cane gives more tonnes per hectare and a perennial stand but demands frost-free land and huge water; beet gives a temperate alternative that fits ordinary mixed farms, at the cost of annual tillage, seed, rotation discipline and a crushing season compressed into a few winter months. Every beet-growing country chose this deliberately, usually with state encouragement, because it made sugar at home instead of buying it from the tropics. Chapter 12 compares the farm economics directly, and Part XI takes up the protectionism that choice created [S2c, S6].

Chapter 11 - The harvest

Sugar is won or lost in the days between field and factory. Cut cane begins losing sugar at once, and the damage a mechanical harvester does to the stalk speeds the loss, so the harvest is run as a campaign: a continuous, district-wide rush to move the crop from standing stalk to crushed juice before its sweetness drains away [S2b]. Beet farming names the same pressure openly: the harvest-processing season is simply called "the campaign," factories running around the clock for months while the roots come in [S2c]. This perishability is the hidden hand behind the industry's geography and its labour history alike. It is why mills sit among their fields, why harvest labour is hired in seasonal surges, and why, for centuries, planters reached for coerced workers who could be driven at the pace the crop demanded. Part XI confronts that labour story; this chapter is about the work itself.

The hand harvest defined cane work for four centuries [S2b]. The sequence begins with fire: the standing field is burned to clear the dry leaves and flush out snakes, leaving the stalks unharmed. Then the cutters go in with cane knives, slicing each stalk near ground level, topping it, and stacking it for collection [S2b]. It is among the hardest regular work in agriculture, done in heat, paid by output, and it persists wherever wages are low, terrain is rough, or farm structure blocks machines.

The machine that changed this is the chopper harvester: it cuts the stalk at its base, strips the leaves, chops the cane into short billets, drops them into a transporter running alongside, and blows the leafy trash back onto the field as mulch, at about a hundred tonnes an hour [S2b]. The modern form descends from Australia's Austoft 7000 series, a design so successful that competitors, including Cameco and John Deere, built their own versions of it [S2b]. Louisiana shows how fast the switch could come when labour forced it: sixteen whole-stalk harvesters worked the state's crop in 1938; by 1946, under wartime labour shortage, 422 machines cut 63 percent of it [S-M5]. Mechanical harvest ends the pre-harvest fire, and the green-cane harvest it enables leaves a mulch blanket that changes field ecology, one thread in the environmental account of Chapter 37.

The machine's own history is Australian, with a contested chapter. Growers and engineers around Bundaberg worked on harvesters from 1908; in 1929 a machine taken to Cuba was converted to chopper operation, which an Engineers Australia heritage citation calls the first commercial application of chopper harvesting in the world, an Australian invention commercialised abroad [S-C12]. The first chopper harvester built in Australia followed in 1934; the Toft brothers of Bundaberg built the first commercial whole-stalk loader in 1941, the

commercially successful Model 250 in 1957 and the first over-the-row harvester in 1963; and Massey Ferguson's tractor-mounted chopper of 1958 carries a disputed credit, the heritage record naming its builders Douglas, Woods and Gaunt, other accounts the Rossi brothers a year later, a conflict this book flags rather than settles [S-C12, S-C10]. Machines split into two families that treat the crop differently: whole-stalk harvesters deliver intact stalks, gentle on the cane but demanding of transport; choppers deliver billets, dense to haul but wounded, and the wound is where the sugar loss begins [S-C10, S-C26].

Mechanisation moved the bottleneck rather than removing it. A chopper harvester is only as fast as the transport chain behind it: infield transporters, road trucks, cane railways and mill-yard handling must absorb that stream, and the mill itself must crush day and night for the season [S2b]. The beet campaign runs on the same logic with different machinery: topping, lifting and loading six rows at a pass, clamping the surplus, and feeding factories that swallow the district's crop in one winter sprint [S2c]. Chapter 33 follows the logistics onward, from mill yard to bulk terminal.

The fire has numbers as well as ethics. Burning removes about 80 percent of the trash and raises harvesting efficiency 30 to 40 percent; it raised a hand cutter's daily output from about six tonnes to nine [S-C10, S-C13]. Queensland adopted pre-harvest burning widely from the 1940s, partly against Weil's disease, a rat-borne infection of cane cutters, and then led the retreat: green-cane harvesting returned from 1976, and more than 85 percent of the state's crop is now cut green, the trash blanket left on the field to hold moisture, suppress weeds and stop erosion [S-C13, S-C10]. The green system is a genuine agronomic package with a price: cutting rates run at 60 to 70 percent of burnt rates, fuel use climbs by an eighth to a sixth, cane losses in the field rise, and on poorly drained or frost-prone blocks the trash blanket fails outright [S-C13, S-C10]. Policy is closing the fire anyway: Sao Paulo State's Law 11.241 of 2002 mandates the gradual elimination of pre-harvest burning, defining which land counts as mechanizable and setting buffer bans around towns, reserves and infrastructure [S-C27]. The distinction between legal deadline and voluntary pledge is documented: in 2007 the mills' association signed a state protocol to end burning by 2017, well ahead of the law's own 2031 target, with mills crushing over half the state's output signed within months [S-C32, S-C27].

Perishability governs the end of every chain, and its science is precise. Cane deteriorates from the moment of harvest, whether it was cut green, cut after burning, or burnt and left standing; the pace is set by weather, fastest in hot, humid conditions [S-C26]. The patterns differ in instructive ways. Green-cut cane keeps its sugar longer overall, yet its juice quality dips fastest in the first days as sucrose converts to reducing sugars. Cane burnt and left standing

deteriorates fastest of all under moist soil conditions, the scorched plant drawing up water and diluting its own sugar, which is why field supervisors burn only a day's allocation ahead of the cutters [S-C26]. Physical damage is the great accelerator: chopper billets, about 300 millimetres long as a compromise between load density and deterioration, lose sugar faster than whole stalks, and short, smashed billets lose fastest of all [S-C14, S-C26, S-C8]. How fast is fast varies by system: in Australia, where all cane is machine-harvested, the allowable cut-to-crush delay before penalties is generally not more than twelve hours, a local contract practice rather than a universal limit, while delays of three to four days remain common in South Africa at direct revenue loss [S-C26]. Every hour between cutting and crushing is paid for in sugar that never reaches the pan [S-C14].

The beet side of the campaign answers perishability with patience, and patience has its own meter running. A lifted beet is alive and breathing: respiration burns its stored sugar, fastest in the first days of wound healing after the trauma of lifting, then settling to a rate driven by temperature, lowest between about 2 and 8 degrees Celsius [S-C21]. Stored beets bleed quality in other ways too: invert sugars accumulate and complicate factory processing, sprouts and rots take their share, and a frost-damaged beet cannot be stored at all [S-C21]. The storage craft is therefore a set of disciplines: lift gently, top completely but shallowly, ventilate the clamp, treat against pathogens with lime where practice allows, and track the accumulating loss on degree-days so the oldest, warmest clamps are processed first [S-C21]. Cane must race the clock in hours; beet buys itself weeks and pays a slow tax for every one of them.

Chapter 12 - Farm economics

Sugar farming is not one business but many, and the differences decide who survives a price swing. At one pole stand estate plantations and mill-owned farms, where growing and crushing are one operation and the cane never changes hands. At the other stand independent growers, from Brazilian suppliers to Indian smallholders to European beet farmers, who sell their crop to a factory they do not control. Between them sit cooperatives, especially in beet countries, where the farmers own the factory itself. The structure matters because cane and beet are crops with a single buyer in reach: perishability chains the grower to the nearest mill, and the mill's terms, not a spot market, set the grower's price. How those terms are set, revenue-sharing formulas in some countries, state-set cane prices in others, contracts in the beet belt, is a political story as much as a commercial one, and Part XI takes it up. Queensland's formula shows the mechanics at their most transparent: the cane price is a function of the cane's CCS sugar content and the season's Net Sugar Price, where the Net Sugar Price is the ICE No. 11 outcome plus marketing premiums minus marketing costs, the futures market supplying about 99 percent of the net price on Queensland Sugar Limited's five-year average [C52]. The world price of Chapter 31 reaches the grower's bank account through arithmetic like this.

What the farmer actually sells, though, is not tonnes but recoverable sugar, and the two crops measure it differently. Australian cane growers are paid on measured quality: brix, the dissolved solids in the juice; pol, the polarimetric estimate of true sucrose; and CCS, "commercial cane sugar," the composite figure on which the cheque is written, averaging about 13 percent and reaching 18 in the best cane [S-C2]. A system like that rewards farming for sugar, not just bulk: it pays to ripen properly, harvest clean and deliver fast. Beet payment systems run on the same principle through their own arithmetic, sampling roots for sugar content and deducting for the dirt and tares that arrive with them. On either crop, the grower's real product is a perishable, quality-graded biological material delivered to a monopsonist on a schedule the factory sets. Everything else in this chapter is commentary on that sentence.

The yield league tables give the structure its numbers. Cane's 2024 leaders, on FAOSTAT-based data republished by two independent aggregators whose figures match to the tonne: Senegal at 114 tonnes per hectare, Malawi and Egypt around 107, Guatemala 105, then the big mechanised producers, Australia at 88, the United States 84, China 81, India 79 and Brazil 76, with Thailand at 55 and Cuba at 33 [S-C20, S-C34]. Beet's 2024 table is led by Chile at 94 tonnes per hectare, then Germany 84, France 79, Britain 76, the United States 73, with Poland at 66, China 57 and Russia, after a decade of steep improvement, at 47 against a global median near 51 [S-C19, S-C34]. FAO's reference ranges put

rainfed humid-tropic cane at 70 to 100 tonnes per hectare and well-irrigated cane at 110 to 150, with sucrose at harvest usually 10 to 12 percent of fresh weight, which lets a reader convert any of these tonnages into sugar [S-C1]. The rankings carry a lesson: the leaders are irrigated specialists and tightly managed temperate farms, not the giants. Brazil wins its crown on scale and logistics, not yield per hectare.

Cost structure decides resilience. In China the cane stalk itself is 60 to 70 percent of the cost of producing sugar, so the grower's price is the industry's central variable, and the ratoon system is the main lever on it: ratoon crops cost 25 to 30 percent less to produce than plant cane, but they yield far less where disease and poor stand management shorten their life, which is why Brazil runs plant cane plus four or five ratoons while parts of southern China keep only one [S-C8]. The farm scale behind these numbers varies enormously. Australian cane farms are mostly family businesses of 40 to 250 hectares, large enough to own or contract machine harvest, small enough to feel every price cycle [S-C2]. India's millions of smallholders sit at the opposite pole, which is why the politics of cane pricing there is a chapter in itself, and Part XI takes it up.

Beet economics is a defensive game. Europe is projected to remain the main beet region, but production there is capped by shrinking availability of plant-protection products and competition for land from more profitable crops; of the major beet producers, only Russia is expected to expand output [S22]. The beet grower's competition is not the tropical plantation across the ocean so much as the wheat or rapeseed field next door: beet must out-earn alternative crops on the same land, which is why the industry has always leaned on contracts, cooperatives and policy support. The European sector's own statistics describe a consolidating industry: 85 factories operational in 2023-24, eighteen fewer than when quotas ended in 2017, serving 98,070 growers after more than 43,000 had exited in a decade, with sugar yields of 11.4 tonnes per hectare and prices that swung from under 350 euros per tonne in 2019 to over 900 in 2023 before falling back [S-C18]. A crop that must justify its place in the rotation every single year cannot afford a bad decade, and beet has had several.

The macroeconomic frame, though, is global, and it is documented. The OECD-FAO Agricultural Outlook projects world sugar production expanding about 14 percent over the decade to 2033, with sugarcane supplying more than 85 percent of the sugar crop [S22]. Within that, the centre of gravity is fixed: Brazil and India are projected to account for about 23 percent (46 million tonnes) and 19 percent (38 million tonnes) of world sugar output in 2033, with Thailand the other major gainer [S22]. Brazil's dominance rests on a structural advantage no beet country shares: its mills can swing production between sugar and ethanol as relative returns shift, a built-in flexibility that lets the sector ride out price

cycles that bankrupt less adaptable producers [S22]. The Outlook expects market conditions to favour export-oriented sugar production over ethanol through the period, though biofuel policies elsewhere, notably India's E20 blending programme, pull cane away from sugar [S22].

Cost data across regions is genuinely hard to compare. What the sources support is structural: cane's advantage is yield per hectare and ratooning; beet's is fitting high-value temperate rotations with mechanised labour; Brazil's is scale plus the ethanol option; and every grower's fate is tied to a world price they do not set. Chapter 31 tells the price story itself, including what the cycles did to each kind of farm.

PART V - FROM PLANT TO CRYSTAL

Chapter 13 - The mill: extracting the juice

A sugar factory begins with destruction. The cane arriving from the fields must be torn apart so completely that its juice can be washed out of the fibre, and the machine that does it descends in a straight line from one of the oldest industrial mechanisms on earth: the roller mill. Before rollers, cane was squeezed in beam and screw presses or ground in edge-runner mills; the vertical three-roller mill became the defining machine of the early modern sugar estate [S-M4].

Where that mill came from is still argued about, and the argument is worth recording because it shows how a tidy origin can survive on authority alone. For most of the twentieth century the standard accounts, following Edmund von Lippmann's 1890 history and repeated by Noel Deerr, credited one Pietro Speciale of Sicily with inventing the three-roller mill in 1449. In 1955 the Brazilian scholar Moacyr Soares Pereira showed the Sicilian story was assertion without evidence, and proposed instead that the horizontal two-roller mill came from Asia and gained its third roller, turned vertical, in Brazil; the controversy was carried into English by John and Christian Daniels in Technology and Culture, who called the 1449 claim a dogma. This book reports the dispute and settles nothing [S-M10]. What is not in dispute is the machine's standing: Joseph Needham placed the cane mill, with the cotton gin, among "the ancestors of all steel-rolling mills, mangles and paper or textile machinery" [S-M10].

The British industrial revolution took the mill into iron. In 1754 John Smeaton, the century's most famous engineer, was credited with the first "modern" horizontal sugar grinding mill, built for a Jamaican producer; by 1794 John Collinge had produced many more [S-M4]. Refinement followed refinement: John Fleming's 1773 "trash turner" patent carried the crushed bagasse from the first roller pair to the second without hand-feeding, the conceptual ancestor of the automatic feeders in modern mill sets [S-M4]. In Scotland and the English Midlands the machine-builders were soon exporting to the cane world; Chapter 18 maps that industry [S-M4]. In 1830 the Jukes and Coulson mill surpassed the Collinge design with screw-adjusted roller spacing and a detachable head for fast replacement of worn parts [S-M4].

The mill was also a dangerous place to stand. Accounts of the period describe a cutlass kept within reach of the rollers, ready to sever a worker's arm if clothing or a hand was drawn in [S-M2]. Every device that kept hands away from the rolls - the trash turner, the preparing rolls, the mechanical feeder - was a safety machine as much as a production machine.

Power came next, and here the sources disagree by a generation. The Sugar Association's timeline, citing Veront Satchell's study of the early use of steam in Jamaica, dates the first steam-powered sugar mill to that island in 1768 [S-M5].

The historian G. Roger Knight, in Sugar, Steam and Steel, records the first stationary steam engine erected in "the colonies" as Cuba in 1797, with steam mill engines spreading through Cuba and the British Caribbean in the following decades [S-M11]. The two claims turn on different definitions of "first", and this book records the disagreement rather than settling it. What is documented is the export wave that followed: between 1803 and 1825 Boulton & Watt shipped 119 engines to the sugar colonies, and the Liverpool firm of Fawcett & Littledale shipped 148 between 1813 and 1825 [S-M11]. Knight frames the transformation as three changes at once: far better grinding of the cane, revolutionary improvement in cleansing and reducing the juice, and the turning of sugar making from an art into a science [S-M11]. The first of those is this chapter's subject; the other two belong to the next.

The modern mill is the descendant of all of this: a tandem of several three-roller mills in series, the cane mat passed from one to the next while water or thin juice, called imbibition, is sprayed against the flow to wash out the sugar [S-M34]. Its rival is the diffuser, borrowed from the beet industry, in which prepared cane percolates against hot water in a long trough or tower; the first bagasse diffuser dates to 1966 in South Africa, built on the precedent of Egyptian diffuser practice [S-M5]. The beet industry had built the design families first: the horizontal rotating RT diffuser, named for Raffinerie Tirlemontoise; the inclined-screw DDS, for De Danske Sukkerfabrikker; and the vertical-screw tower, whose modern plants reach 17,000 tonnes of beet a day, the cossettes spending about ninety minutes against the water [S-M27]. A vendor engineering comparison for a 10,000-tonne plant puts combined extraction-and-clarification efficiency at roughly 94 percent for a mill tandem against 96 percent for a diffuser - a builder's case study, cited here as an indication of how close the contest is, not a verdict [S-M25]. Either way, the factory's first goal is the same as the first millwright's: break the cane, take the juice. What happens to the juice next is the story of fire, and of how sugar tamed it.

The cane itself enters the mill as roughly 13 to 15 percent fibre by weight, the cellulose-hemicellulose-lignin skeleton that becomes bagasse [S41]. Factory size is denominated in TCD, tonnes of cane per day: an Indian training text puts the average crushing capacity of that country's mills at about 4,000 TCD, with size classes from under 1,250 upward [S41]. The mill's own quality control runs on ratios: the Java ratio, which sets the cane's pol content against the pol of the first expressed juice, gives the simplest indirect measure of cane quality [S41].

A snapshot from 1911, preserved in the Britannica's engineering article of that year, shows the mature steam-era factory as its practitioners knew it. A mill shown at the Paris Exhibition of 1900 carried three rollers 32 inches in diameter

by 60 long, driven through triple gearing of 42 to 1, and was guaranteed to crush 250 to 300 tons of cane in 24 hours; a Louisiana tandem of two such mills, 32 by 78 inches, driven by one engine through 15-to-1 gearing, was crushing 900 to 1,200 tons [S-M34]. Estates no longer relied on one crushing. Double crushing with maceration had been used on a commercial scale first in Demerara under William Russell; Hawaii went to triple crushing; favoured spots in the south of Spain used four [S-M34]. The maceration itself - wetting the bagasse between crushings with water or steam at 20 to 40 percent of the cane's weight - cut the juice lost in the fibre by about half [S-M34]. Ahead of the first mill stood grooved preparing rolls that flattened the incoming cane however it was heaped on the carrier, ending the choke-stoppages of hand feeding [S-M34]. Mechanical cane feeders displaced 64 hands on a single 1,200-ton West Indian estate, and were almost universal in Louisiana [S-M34]. And because a crowbar dropped into the rollers could wreck a season, hydraulic rams on the roller bearings, an attachment invented by Jeremiah Howard and described in the United States Patent Journal in 1858, let the rolls lift over tramp iron while a weighted accumulator held the crushing pressure constant [S-M34]. The best estates of that year made twelve and a half percent sugar on cane where Louisiana managed seven to nine and irrigated Hawaii twelve to fourteen [S-M34]. These are period values, a benchmark of what 1911 called good, not modern figures.

Chapter 14 - Clarification and evaporation

Juice fresh from the mill is a dirty, unstable liquid: cloudy with fibre and soil, carrying proteins, gums and acids, and spoiling by the hour. The factory's next two jobs are to clean it and then to remove most of its water, and both jobs run on heat. For most of sugar's history that heat was crude and dangerous. The classic early-modern arrangement was the "Jamaica train": four or five open copper kettles of decreasing size in a row over direct fire, the juice clarified with lime and sometimes ox blood, skimmed and ladled from kettle to kettle by hand. Scalds, burns and fire were routine hazards of the boiling house [S-M2].

The first great taming of the fire came from a London chemist. In 1813 Edward Charles Howard patented the vacuum pan: a closed, steam-heated vessel held under partial vacuum, exploiting the fact that water boils at lower temperature under reduced pressure. Juice could now be concentrated without the scorching that caramelised sugar and darkened the product [S-M2, S-M3]. The patent, British Patent 3754, was an instrumented specification, not just a vessel: it described the air pump and injection condenser that held the vacuum, a thermometer immersed in the liquor, a proof stick for reading density, and a table of boiling points from 115 to 175 degrees Fahrenheit against the vacuum gauge [S-M34]. Howard's pans were manufactured by Boulton & Watt and adopted by European refiners and American plantations; a sugar-industry heritage source dates the patent to 1812, but three fully read accounts, including the 1911 Britannica's description of British Patent 3754 of 1813, agree on 1813, the date this book uses while noting the outlier [S-M2, S-M3, S-M34, S-M30]. Howard died in 1816, only forty-two years old; his royalty income that year was reported to exceed 60,000 pounds, a figure the record repeats without showing its workings [S-M2]. Dudley Newitt, in his 1951 presidential address to the Institution of Chemical Engineers, called Howard "the first chemical engineer of any eminence" [S-M2].

The second taming was Norbert Rillieux's, and it is the single most consequential invention in the sugar story after crystallisation itself. Rillieux was born in New Orleans in 1806; his birth record reads "quadroon libre, natural son of Vincent Rillieux and Constance Vivant," his mother a free woman of color, his father a plantation owner and inventor who acknowledged his son publicly and sent him to Paris [S-M1]. By twenty-four he was an instructor in applied mechanics at the Ecole Centrale, publishing papers on steam engines and steam power around 1830 [S-M1]. He knew the boiling house from his father's plantation, and he brought thermodynamics to it. His insight was that the vapour rising off boiling juice is not waste but fuel: taken from the first vessel and condensed in the heating chest of a second, held at lower pressure so its liquor boils at a lower temperature still, the same heat can evaporate water

two, three, four times over [S-M1, S-M2]. His multiple-effect evaporator, patented in the United States in 1843 and described in an 1846 patent as a series of vacuum pans "so combined together as to make use of the vapor of the evaporation of the juice in the first, to heat the juice in the second," with the last connected to a condenser, brought Rillieux an 1843 commission to install the system on Judah Benjamin's Bellechasse plantation [S-M1]. The fuel economy transformed the cost of sugar, and the system was adopted in Cuba, Mexico, France, Egypt and across the United States [S-M1]. The engineering historian John Heitman called it "the premier engineering achievement in nineteenth-century sugar technology," and the American Chemical Society has designated it a National Historic Chemical Landmark [S-M1]. The principle outgrew sugar entirely: multiple-effect evaporation under vacuum remains standard across the process industries, from condensed milk to soap and glue [S-M1].

Rillieux's own life refused the technology's smooth path. Free though he was, a man of color could be neither lodged nor entertained on the plantations that hired him - in a contemporary's words he was the most sought-after engineer in Louisiana - and as the Civil War approached he was required to carry a pass in his own city [S-M2]. He returned to France, became principal of the Ecole Centrale, gave up engineering for Egyptology, and made one late return in 1881, proposing a multistage system for beet processing and a cane diffusion process for Egypt; neither won support, and the cane diffusion idea he sketched would wait half a century for its industry [S-M2]. He died in Paris in 1894 [S-M2].

The hardware that evolved from these inventions still stands in factories. The "Robert" evaporator, the vertical-tube calandria design developed by the Moravian beet-sugar manufacturer Florentin Robert at Seelowitz from 1850, remained a standard apparatus in the beet industry for over 120 years and is still the reference design for cane factories because of its tolerance of scale [S-M30, S-M29]. It is a rising-film calandria: juice climbs inside vertical tubes while steam condenses around them, and its virtues are robustness and simplicity - generations of factories have, in a modern specialist's words, basically designed their own [S-M29]. Its operating subtleties are real: boiling-point elevation and the hydrostatic head of juice in the tubes set the true boiling temperature, and heat transfer depends strongly on holding the juice near its optimum level, around 30 to 35 percent of tube height in the first effect [S-M29].

The newest chapter is the falling-film evaporator, in which juice descends as a thin film inside the tubes instead of rising as a boiling column; with no hydrostatic head, the same thermal power can be had at lower temperatures, and steam-bleeding schemes can be rearranged to cut steam use [S-M20]. Standard in beet factories for more than thirty years, it was long avoided in cane because cane juice scales heating surfaces - scaling and non-condensable gases are its

enemies, managed by cleaning intervals and proper venting [S-M19]. The first documented cane evaporator set built entirely of falling-film effects was commissioned in January 2012, a five-effect plant that held 7,000 tonnes of cane per day at about 33 percent steam on cane, with third-effect vapour supplying the pans [S-M19]. Clarification chemistry advanced alongside: the beet industry adopted carbonatation, the process Chapter 16 gives its own history, and plate-and-frame filtration, both in 1863 [S-M3]. The boiling house of the Jamaica train had become a closed, instrumented heat engine. A standard modern train shows the whole discipline in numbers, documented in an Indian National Sugar Institute process text: raw juice heated to 70 degrees Celsius, treated with lime and sulphur dioxide in a sulphiter to pH 7.1, heated again to 102-103, then held in a clarifier for two to three hours while the mud settles out; the clear juice then goes to the evaporator set and comes out as syrup at 60 degrees Brix, sulphited once more to pH 5.0 against colouring before the pans [S41]. Every parameter there is a compromise between destroying impurities and destroying sugar.

Chapter 15 - Crystallization

Everything in the factory aims at one event: persuading sucrose out of solution as crystals. The concentrated syrup from the evaporators goes into the vacuum pan, where further boiling under reduced pressure pushes it past saturation; seeded correctly, the syrup grows a crop of crystals suspended in thick mother syrup, a mixture the factory calls massecuite. For over a century this was a batch craft, pan by pan, judged by the pan-boiler's eye [S-M21].

The practitioners of the batch era were proud of it, and suspicious of mechanising it. The engineering writers of 1911 argued that evaporating a given weight of water always requires condensing at least the same weight of steam - in practice about fifteen percent more - so mechanical agitators and elaborate multi-point feeding added cost and maintenance without adding capacity. A skilled sugar boiler, they insisted, could boil 150 tons of hot raw sugar in a pan in a few hours, fed through a single pipe and valve ten inches across; the efficient pan was a simple one, its heating coils kept to fifty or sixty feet in length and arranged so the cooking mass rose over the coils and fell again by natural circulation [S-M34]. The argument matters because it shows the craft's economics: crystallisation is a heat problem as much as a chemistry one, and every embellishment had to pay its way in steam.

The batch pan has not disappeared: vendor control libraries still ship templates for batch vacuum pans alongside continuous crystallisers, fed steadily instead of filled and emptied [S-M22]. The craft element has not vanished; it has been instrumented. Continuous vacuum pans came first in a horizontal layout, which the cane industry still mostly uses; the newer interest is in vertical continuous pans with mechanical agitation, which can hold circulation while boiling on low-pressure vapour bled from the later effects of the evaporator set - one more move in the steam-economy game that Rillieux began [S-M21].

Crystals in syrup are not yet sugar. The separation of crystal from molasses is the centrifuge's work, and its invention history is the messiest in the whole factory, so this book gives it as the record stands: contested. The first industrial centrifugal patent was French, Penzolt's of 1837, and it was built to dry wool, not sugar; the first sugar-industry application followed in 1844 [S-M3]. A Shotter and Dubrunfaut machine appears in 1848, and 1852 is the year usually attached to David Weston, a Boston machinist working in Hawaii [S-M24]. That 1852 date comes with a documented warning: the patent the Sugar Association cites for it, US236389A, actually dates from 1881 and covers an improvement, a stationary plough that detaches the sugar wall from the spinning basket automatically [S-M28]. A Hawaiian newspaper account records Weston brought out in 1851 to erect the Lihue plantation's mill, inventing his "Centrifugal

Separator" at East Maui that year, and founding the Honolulu Iron Works in 1852, which built sugar machinery for decades [S-M33]. Weston clearly patented the first suspended centrifugal in 1867 and was central to making the machine practical [S-M3]. The honest summary: the sugar centrifuge emerged between 1844 and 1867, credit is split between the French pioneers and Weston, and the tidy "Weston 1852" story does not survive contact with the patent record [S-M3, S-M28, S-M33].

The machine mattered because of time and yield. Draining molasses from sugar in cones took weeks; the spinning basket did it in minutes [S-M33]. Early machines still took muscle: the 1881 plough patent exists because discharging each charge had meant two or more men spading the sugar wall off the basket by hand [S-M28]. Specialist firms grew up on it - Broadbent of Huddersfield, Western States of Salt Lake City, BMA of Braunschweig - and Chapter 18 tells their story; BMA's model genealogy alone documents the continuous centrifuge's evolution machine by machine from 1958 onward [S-M9, S-M8, S-M6]. The process consequence outweighs the model numbers: continuous centrifugation pulls more sugar from each charge and leaves less in the molasses, a gain one industry technical review calls one of the major advancements of the cane industry [S-M23]. Broadbent's current batch machines reach up to 60 tonnes per hour [S-M9].

One boiling rarely exhausts a syrup. Factories boil in series, a scheme the process texts show as A, B and C massecuites: the first strike from syrup gives the best crystals, its molasses is reboiled for a second strike, and the third, lowest strike is squeezed for the last recoverable sugar before the mother liquor leaves the factory as final molasses; the small low-grade crystals are remelted and returned to the process [S41]. From massecuite to dry crystal, what remains is drying, grading and, for most of the world's sugar, a second purification far away: refining.

Chapter 16 - Refining

The sugar leaving a cane mill is raw: golden-brown crystals, sticky with residual molasses, stable enough to ship but not to sell on a European or American table. Turning it white is a separate industry, historically located at ports near consumers rather than fields near cane, and the split between milling and refining shaped sugar's whole commercial geography, as Part IX tells. Refined white sugar, the end point, is about 99 percent sucrose [S2b].

The old refinery was a craft of blood, lime and patience. Raw sugar was dissolved in a copper boiler with bullock's blood and lime water; as the liquor heated, the albumen coagulated and entangled the mechanical impurities in a scum that was skimmed away. The clarified syrup was boiled to a thread, granulated in open coolers by stirring with wooden oars, and set in moulds to drain into loaves [S-M32]. Everything in the modern refinery is an answer to one of those steps.

The first step in the modern sequence is affination: the raw crystals are mingled with hot affination syrup into a magma, spun so the molasses film washes off the crystal faces, and then melted back into liquor. The machinery is documented in detail - a mingling trough, centrifuges that wash the crystals in the basket with water above 82 degrees Celsius, and a melter tank where the washed crystals dissolve into sweetwater - and the step has become compact enough that by 1991 a single continuous machine could perform the affination and the melting in one body [S-M32, S-M6]. Some modern refineries buying high-polarity raw sugar skip affination altogether [S-M32]. Then comes clarification, and with it the refiner's core problem, colour. The war on colour has a chemistry of its own. Vegetable charcoal was noted for decolorising as early as 1785, and an English refinery was using charcoal on raw sugar by 1794 [S-M12]. Charcoal helped make the infant beet industry viable: it was among the improvements behind Delessert's practical success with beet sugar at Passy in 1808, the success that moved Napoleon to order more factories built [S-M12]. But bone-black, roasted and ground animal bone, proved far stronger from 1812 and became near-mandatory in refineries for decades - so much so that in 1836 Boettcher was recommending brown coal for sugar bound for the East Indian market, where, as the refinery chemist Zerban later recorded, Hindu buyers had religious scruples about sugar made with the aid of bone-black [S-M12]. The proprietary vegetable carbons that followed, Norit and Eponit, showed ten to thirty times bone-black's decolorising power, and refineries standardised the practice of reviving spent carbon by caustic boiling or reburning [S-M12]. Modern refineries clarify with carbonatation or phosphatation and then decolorise through columns of bone char, granular

activated carbon or ion-exchange resin, columns twenty-odd feet tall that polish the liquor to water-white before it goes back to the pans [S-M32].

Two beet-industry inventions round out the toolkit. The first is carbonatation itself, the simultaneous injection of lime and carbon dioxide that precipitates impurities, introduced in 1863 [S-M3]. The second is molasses desugarisation. Beet molasses kept half the sugar the factory had failed to crystallise, and Carl Steffen, a Vienna-born chemist working in Moravia, patented the answer in 1883: dilute the molasses to a thin solution, chill it below 18 degrees Celsius, and work in finely powdered lime, which binds the sucrose into an insoluble calcium saccharate; filtered out and returned to the process, the saccharate did double duty as its own defecant [S-M13]. Factories with a Steffen house recovered about 90 percent of the sugar in their beets instead of losing it to molasses, and the American factory builder Henry Oxnard would not accept a contract for a factory without one [S-M13]. The first American Steffen installation ran at Watsonville, California, from 1888, on a pilot plant supplied by the Grevenbroich Machinery Company of Germany; Cleveland's Kilby Manufacturing later built improved models [S-M13]. The process carried a fatal flaw: it discharged alkaline, malodorous wastewater in volumes up to eight hundred percent of the molasses treated, and from the 1970s, as that effluent became unacceptable, it yielded to ion-exclusion chromatography, a separation technology adapted from the corn-syrup industry that recovers on the order of ninety percent of the molasses sugar against Steffen's sixty, without the smell [S-M13]. The chromatographic route then had its own engineering history. The first industrial-scale batch system in America ran from 1973 at the Utah-Idaho Sugar factory in Moses Lake, Washington, a single column holding 22 cubic metres of resin; batch operation was short-lived, replaced by simulated moving bed technology that achieves the same separation with less water and less resin, and the first commercial SMB installation in the United States followed in 1988 at Amalgamated Sugar's Twin Falls, Idaho factory [C113]. The technology split molasses into a sucrose-rich extract sent back to the pans and a non-sugar raffinate, then grew more ambitious: Finnsugar's 1989 sequential process added a purified betaine stream, and Amalgamated Research's 1997 coupled-loop design recovered betaine without extra resin or water [C113]. The performance curve is documented by the firm that builds them. Amalgamated Research reports the Z-factor, its composite measure of how much of the feed molasses's sugar the combined separator-and-crystalliser loop wins back, at around 75 percent for an efficient early system and above 80 percent for modern ones, and says its own units now run at up to eight times the 1988 baseline's non-sugar loading per unit of resin; most American beet companies now operate a desugarisation system [C113]. Ion-exchange treatment of the juice itself, the

Quentin process, attacks the same problem from the other side, reducing the impurities that drive sugar into molasses in the first place [S-M23].

Refining's history also carries sugar's recurring theme of concentration. The refineries were fewer, larger, more capital-hungry and closer to the consumer than the mills, and they bred sugar's greatest business empires: the Havemeyers in New York, Tate and Lyle in London and Liverpool, the port refiners of Hamburg and Antwerp [C18, C16, S31]. Their story, including the Sugar Trust that swallowed ninety-odd percent of American refining by 1891 and survived the Supreme Court in 1895, belongs to Chapter 28 [C19, C20]. The boundary between raw sugar and white, between mill country and refinery country, is where the commodity of Part X is made.

The product's final form has its own history. Until the mid-nineteenth century, sugar left the refinery as loaves and cones, cut at the table with sugar nips. Granulated sugar, the free-flowing crystals that replaced the cone and the loaf, is credited to the Boston Sugar Refinery in 1853: moist refined sugar was raked across steam tables until dry, then sieved into grades [S-M31]. Charles Hersey of South Boston patented a granulating machine in 1871 that became standard refinery equipment, and later a sugar-cube machine; the refinery itself was absorbed into the Sugar Trust in 1887 [S-M31]. The cube, the sachet and the bag on the kitchen shelf are all descendants of that shift from loaf to grain.

Chapter 17 - Energy in the factory

A cane factory's first fuel is its own residue. The mill's mass balance makes the quantities concrete: cane plus the imbibition water sprayed against it leaves the mills as mixed juice and bagasse, and in the process textbook's worked example the bagasse amounts to about 30 tonnes for every 100 tonnes of cane [S41]. The textbook's flow diagram runs that bagasse straight to the boiler, the boiler's steam to the turbine [S41]. Supplementary fuel enters where the residue loop is stretched: the Mauritian export-power programme's stations, for example, were designed as bagasse-and-coal plants [S-M17].

The steam from the boilers does its work in the factory two ways in the textbook's flow: it supplies the process heat of juice heating, evaporation and boiling (Chapters 14 and 15), and it spins the turbine that generates electricity [S41]. How much power, if any, a factory can sell beyond its own demand is an engineering and commercial question, not an automatic property of the crop. The Mauritian programme's own design documents put it exactly so: the aim was to increase the efficiency of generation and of power use inside the factories, in order to free the incremental bagasse surplus for export [S-M17].

The documented extreme of the surplus is Hawaii. A 1990 United States government technical report on Hawaiian cogeneration records that the islands' sugar factories produced nearly all their own steam and electricity for close to a century and still exported about 400 million kilowatt-hours a year to the public utilities: on average about 60 kilowatt-hours per ton of cane, some factories over 100, against a worldwide industry figure near 10, the report's own units and period [S-M16]. The report attributes that performance to decades of technical improvement, better use of the biomass, consolidation of steam raising into fewer and larger units, higher operating pressures and temperatures, and notes that in later years regulatory and contractual arrangements, rather than technology, shaped how much power was generated and sold [S-M16].

Where policy builds the market, the surplus becomes an industry. Mauritius made factory power export a national programme in 1991: the Bagasse Energy Development Programme, born of the country's Sugar Action Plan and backed by the World Bank, set out to multiply bagasse-based electricity and to raise generation efficiency inside the factories [S-M17]. Brazil shows the scale the model can reach. In 2024, total electricity generated for the Brazilian grid was 632,145 gigawatt-hours; biomass-based thermal generation supplied 28,260 gigawatt-hours of it, the fourth-largest generation source, just behind natural gas; and sugarcane bagasse and straw provided 21,218 gigawatt-hours, 75 percent of the biomass total [C98].

The beet factory has no equivalent of bagasse. Its residue is beet pulp, and pulp is a product with three commercial routes rather than a fuel. The press squeezes water from the pulp to make it transportable [C100]; at a pressed dry matter of roughly 24 to 29 percent it is used wet as ruminant feed near the factory, fresh within days or ensiled for longer keeping [C101]. The second route dries it to about 10 percent moisture and pellets it into the storable, year-round feed product [C100, C102]. The third route is energy: pulp feeds anaerobic digesters, fresh during the campaign or stored as silage or bales for the rest of the year. The documented cases are commercial, not experimental. AGRANA's Kaposvar factory in Hungary has run a biogas plant on its own spent pulp since 2007, the by-products supplying a large portion of the plant's energy needs [C103]. British Sugar's Bury St Edmunds digester, designed for about 97,500 tonnes of pressed pulp a year, generates up to 5 megawatts of electricity with heat recovery [C104]. And in 2024 Cristal Union signed a fifteen-year agreement to supply pulp as over half the feedstock for a TotalEnergies biomethane unit then being built in Normandy [C105]. Where pulp is dried, the drying is a major load in itself: drum drying calls for about 98 kilowatt-hours per tonne of beet [C99]. So the beet factory's classic position is to buy its fuel, and its energy engineering is a minimisation problem. One industry engineering paper records the trajectory: from 250 to 300 kilowatt-hours of fuel per tonne of beet down to about 170 for a good factory excluding pulp drying, over the half-century to 2015, with best-practice designs aiming at 140 to 150 including drying, and evaporating crystallisation the largest single energy user in the plant [C99].

The contrast between the two crops is therefore not a slogan but a set of conditions. A cane factory with efficient boilers and a grid that will buy becomes a power exporter; without them it is simply self-supplied, and the documented spread is wide, from Hawaii's 60 kilowatt-hours per ton down to the worldwide figure near 10 [S-M16]. A beet factory without its own residue fuel manages purchased fuel instead, or, in the documented cases above, digests part of its pulp into gas. Chapter 26 takes up what bagasse becomes when it is not burned: paper, board, chemicals and feedstock for the second-generation ethanol of Chapter 25.

PART VI - THE MACHINERY

Chapter 18 - The equipment industry

Behind every sugar factory stands a second industry that most sugar histories skip: the firms that build the machines. Sugar created its own specialist engineering sector, and its geography is a map of the industrial nineteenth century.

Glasgow and the English makers

Glasgow was its first capital. James Cook's workshop, established about 1785, had built a steam-driven sugar mill by about 1815; his successor firm David Cook and Company, under chief designer Robert Harvey, supplied sugar machinery to every part of the world, and when Cook retired, Harvey's own firm took the business over [S-M4]. A. & W. Smith was founded in 1837, P. & W. McOnie in 1840; the McOnies had fifty engines and fifty mills to their name by 1848, when the partnership split, and between 1851 and 1876 the continuing firm of W. & A. McOnie alone built 820 steam engines, 1,650 sugar mills, 1,200 steam boilers, 117 water wheels and 169 evaporating pans [S-M4]. Peter McOnie meanwhile joined James Buchanan Mirrlees in 1848, starting the Mirrlees engine line, and Mirrlees & Tait spawned further firms - Watson Laidlaw, Pott Cassells - whose output was prodigious [S-M4]. Harvey's firm and a McOnie descendant merged in 1888 as McOnie Harvey and Company, which by 1908 had become Harvey Engineering, specialising in Harvey's patented evaporator [S-M4]. Around them grew a cluster - Blair, Campbell and McLean, Duncan Stewart, A. F. Craig, John McNeil - most of it absorbed after the Second World War into A. & W. Smith, by then part of the Tate & Lyle group; Duncan Stewart's sugar business passed to Fletcher & Stewart [S-M4].

Liverpool sent Fawcett Preston's engines and mills to Cuba from 1816-17; London's George Fletcher began in Lambeth about 1840, moved to Southwark in 1847, and his line passed to Fletcher & Stewart of Derby [S-M4]. In the 1820s the Butterley Company of Derbyshire was already shipping sugar milling machinery to the West Indies and Mauritius [S-M4].

France: Derosne, Cail and the road to Fives

France's industry was born from the blockade itself. Charles Derosne, a chemist, founded workshops in Paris in 1812 for sugar-refining and distillation equipment, at the moment the Continental Blockade cut France off from Caribbean cane [S-M15]. His apprentice Jean-Francois Cail became partner in 1836 and successor in 1846, building complete sugar plants for Cuba, Mauritius and Reunion; by 1847 the firm ran four production sites with more than 2,000 employees, and in 1850 it was the second-largest builder of steam locomotives

in France - sugar machinery and railway iron grew up in the same sheds [S-M15]. After Cail's death in 1871 the firm weakened, went into liquidation in 1882 and again in 1898, emerging from the second collapse as SFCM, which Louis Le Chatelier, son of the scientist Henry Le Chatelier, took over in the 1900s and turned around by 1905; it merged with Fives-Lille in 1958, and the group's 2012 history still counted sugar-processing plant among its continuing activities [S-M15].

Germany: BMA and Buckau-Wolf

Germany's champion was BMA of Braunschweig, founded on 12 April 1853 by four men - the ducal farrier Christian Pommer, the iron merchant Friedrich Seele, the machine maker Friedrich Lorenz Schottler and the railway foreman Wilhelm Hasenbalg - as F. Seele and Company, a wagon works and machine factory [S-M14]. The railway orders were the occasion; the sugar beet was the future. The last wagon left in 1863, and the firm was already building complete turnkey beet factories, riding the diffusion process it had championed: more than a third of all German diffusion plants built between 1864 and 1887 came from its works, where the Raabe rapid apparatus was first installed at Barum, and Schottler bought a closed factory at Einbeck purely as an experiment station [S-M14]. Renamed Braunschweigische Maschinenbauanstalt in 1870, it was exporting up to 85 percent of turnover already in the 1870s; forty-one complete factory plants were finished between 1858 and 1877, including a diffusion factory in California in 1871; three raw sugar factories for Japan went up on Formosa between 1907 and 1911, followed by Harbin, Spain and South America; the company passed four hundred complete sugar factories and refineries delivered by 2003, with spirits-industry plant added to the programme from 1889 [S-M14]. Its compatriot Buckau-Wolf, at Grevenbroich, industrialised the tower diffuser from 1952, with about 170 towers working across the beet countries by 2001 and the largest in its own listing, at Lillers in France, rated at 14,000 tonnes a day under modern automatic control [S-M7]. Grevenbroich's machinery trade reached the beet fields of California earlier than that, through the Steffen-house trade of Chapter 16 [S-M13].

The centrifuge specialists

The centrifuge specialists show the same pattern at machine scale. Thomas Broadbent set up as a millwright in Huddersfield in 1864, built his first centrifuge for wool in 1870 and his first steam-driven extractor in 1875; the firm he left at his death in 1880 registered as Thomas Broadbent & Sons in 1895, the year of its first sugar centrifuges and its first electrically driven extractor, patented Horace Broadbent's centrifugal clutch in 1901, built X-craft midget submarines in the Second World War, and fully automated its machines by 1959

[S-M9]. Western States of Salt Lake City, founded by Eugene Roberts in 1917, was selling to Cuba by 1920 and across the Americas, Europe and Asia within a generation; a 1942 War Department contract for a centrifugal to make war chemicals took it briefly beyond sugar [S-M8]. In Hawaii, David Weston's Honolulu Iron Works, founded in 1852 with the backing of the Lihue plantation's owners, outfitted the islands' mills for generations [S-M33]. These firms' product records are the industry's own archive: BMA's K-series documents continuous centrifugation's evolution machine by machine from 1958 onward [S-M6].

The invisible layer

The equipment industry's newest layer is invisible. Modern factories run on distributed control systems, and the automation vendors now sell sugar-specific control libraries covering batch vacuum pans, continuous crystallisers, centrifuges, filters, falling-film evaporators and ion-exchange units - the vendor's own catalogue, describing what is offered rather than what every factory runs [S-M22]. The direction is documented in the hardware: Buckau-Wolf's Lillers tower was delivered in 2000 with modern measuring and automatic control as standard equipment [S-M7]. And the industry's own past is preserved where it happened: the Oldisleben factory in Germany ran its steam engines and diffusion battery until 1990 and now survives as a museum of the nineteenth-century beet train [S-M30].

Why does a book about sugar give these companies a chapter? Because the equipment industry is where sugar's technological influence on the wider industrial world ran. Noel Deerr, the industry's great historian-technologist, summarised the claim: "how great is the debt of chemical engineering to the sugar industry. Here have either been invented or developed the roller mill, evaporation in vacuo and in multiple effect, the filter press in its manifold forms and the centrifuge" [S-M2]. That is an insider's judgment, quoted as such, and the evidence in Part V shows it is not lightly made. Chapter 19 examines what that machinery did to sugar itself.

Chapter 19 - How machines changed sugar

Chapters 13 to 18 told the machines one at a time, each where it belongs in the process: the roller mill and the coming of steam in Chapter 13, clarification and the multiple effect in Chapter 14, crystallisation and the centrifuge in Chapter 15, the refinery's toolkit in Chapter 16, the factory's energy economy in Chapter 17, and the firms that built them all in Chapter 18. This chapter steps back from the parts to ask what the machinery, taken together, did to sugar.

The first thing it did was scale. Steam freed the mill from the muscle of animals, water and wind, and let factories grow from estate workshops into industrial plants [S-M11, S-M4]. The size of the shift is best said in numbers. A large West Indian estate of 1911 crushed upwards of 1,200 tons of cane a day, in the period source's own units [S-M34]; a single recent beet diffuser processes 14,000 tonnes a day [S-M7]. Plant on that scale is not the estate mill writ large. It is a different kind of object - designed by specialist firms, delivered turnkey, and run as continuous process plant rather than as a season's improvisation [S-M14].

The second thing was cost, and the instrument was heat. Boiling juice in open kettles burned through fuel and burned the sugar with it; the vacuum pan and then the multiple effect turned boiling into a controlled thermal process in which the same heat evaporates water two, three, four times over [S-M2, S-M1]. The fuel economy transformed the cost of sugar, and the control transformed its quality: with the scorching gone, white sugar stopped being an expensive refinery luxury and became a routine product of a well-run boiling house [S-M1]. Chapter 14 told that story, but its end point belongs here. The thermal discipline has since run so far that a modern evaporator set is designed as much to free steam for power export as to concentrate juice: the five-effect falling-film plant commissioned in Karnataka in 2012 holds its 33 percent steam-on-cane figure precisely so the surplus can be sold as electricity [S-M19]. The boiling house that once devoured an island's firewood - Chapter 37 records what that hunger did to Madeira - now sells power to the grid; Chapter 17 follows the energy side.

The third thing was recovery. Every stage of the old process leaked sugar, and the machines closed the leaks one by one. Imbibition cut the juice lost in the fibre by about half [S-M34]. The centrifuge collapsed weeks of draining into minutes of spinning and pulled out sugar the open cones had always surrendered to molasses [S-M33, S-M3]; continuous centrifugation then pulled out more still, a gain one industry technical review ranks among the major advancements of the cane industry [S-M23]. In the beet world the diffuser out-extracts the mill - by one vendor's comparison roughly 96 percent against 94 [S-M25] - and then the factory went hunting in the molasses itself: Steffen houses recovered about

90 percent of the sugar in their beets, and the chromatographic systems that replaced them recover on the order of ninety percent of what even molasses held, against Steffen's sixty [S-M13]. The consequence reaches past the factory gate. Recovery created, and then reshaped, the molasses stream that Part VIII follows into rum, fermentation chemicals and animal feed; how much sugar molasses still contains is now a technology choice, not a fact of nature [S-M23].

The fourth thing was the shape of the industry, and here causality wants care. Bigger, faster, steam-driven factories demanded capital beyond a single planter's means, and the consolidation that followed is the machinery story told in business form. In Louisiana between 1880 and 1900, planters who could not finance modern factories gave way to central factories that bought in cane from other growers [E18]; in Cuba the documented wave came later still, fifty-nine new mills built between 1902 and 1927 on United States investment [E11]. Machinery did not cause that consolidation by itself; abolition, credit and policy pushed as well, and Part IX adjudicates their shares. What machinery contributed was the threshold. Each rise in throughput raised the capital a producer needed to stay a producer, and the threshold was sold as a package - complete factories delivered turnkey by firms like BMA, which had passed four hundred delivered factories and refineries by 2003 [S-M14]. The same machinery sorted geography. It made the temperate beet industry workable - diffusion to get the juice, carbonatation to clean it, the Steffen house to chase the last sugar - while breeding and policy kept that industry alive, as Chapter 12 records [S-M7, S-M3, S-M13]. And it helped split making from finishing: the centrifuge and the refinery's decolorising columns let raw sugar travel as a stable intermediate while white sugar was made near its market, which is where the traded commodity of Part X comes from.

The fifth thing reached beyond sugar altogether. The sugar factory was running what engineering now calls unit operations - evaporation in multiple effect, crystallisation, centrifugation, filtration, adsorption, ion exchange, chromatographic separation - at industrial scale before the discipline that names them existed. The Institution of Chemical Engineers' historical review recognises Howard and Rillieux as two of the most significant figures in the prehistory of chemical engineering [S-M2], and the industry's own historian-technologist, Noel Deerr, listed sugar's gifts to that discipline in the verdict quoted at the end of Chapter 18. The transfer is documented in both directions. Multiple-effect evaporation under vacuum remains standard across the process industries, from condensed milk to soap and glue [S-M1]. The chromatography that now mines beet molasses was adapted from the corn-syrup industry - one sweetener industry borrowing back from another [S-M13]. The equipment industry of Chapter 18 was the vector: the firms that sold Cuba its mills,

Formosa its factories and California its Steffen houses carried the process itself [S-M4, S-M14, S-M13].

Machines also changed what a sugar worker needed to know, though not directly how many workers were needed - the employment reckoning is Chapter 34's, and the field's machines are Chapter 11's. The change in the boiling house was codification. Howard's 1813 specification was already an instrumented one: air pump, condenser, a thermometer in the liquor, a proof stick, a printed table of boiling points against the vacuum gauge [S-M34]. Knowledge that had lived in the pan-boiler's wrist and eye moved into the instrument, then into the controller, and the automation vendor now sells the pan-boiler's eye as a sensor array [S-M22]. Knight's summary of the steam century - sugar making turned from an art into a science - is the boiling-house version of the same shift [S-M11]. Where the machine could not go, the old craft remained: mechanisation reached the field last and changed labour most abruptly, when wartime Louisiana mechanised most of its harvest in eight years [S-M5].

The newest transformation is digital, and it works the same levers. Factories that upgrade now buy distributed control systems, and the automation vendors sell sugar-specific libraries for them - one major vendor's catalogue covers batch vacuum pans, continuous crystallisers, centrifuges, filters and falling-film evaporators, offered features rather than proof of what every factory runs [S-M22]. The direction is visible in delivered hardware: the Lillers tower that started up in 2000 as the vendor's largest, shipped with modern measuring and automatic control as standard equipment [S-M7]. What automation does to the workforce, and to the factories that cannot afford the upgrade, is a question Chapter 40 takes up.

One caution travels with the whole part. Several of its familiar dates are contested in the record itself - the roller mill's origin and the first steam mill's date in Chapter 13, and the centrifuge's tangled credit in Chapter 15, where the tidy "Weston 1852" story does not survive contact with a patent record that offers him in 1881 [S-M24, S-M28, S-M33]. Where the record disagrees with itself, the disagreement is the finding. The machines changed sugar's cost, its purity, its scale, its geography and its knowledge; what they did not settle - who owns the factories, who cuts the cane, who eats the sugar - is the rest of the book.

PART VII - EVERYTHING SUGAR FEEDS

Chapter 20 - Sweetness itself

Sweetness itself is a machine as much as a sensation. On the tongue sits a single receptor pair, proteins called TAS1R2 and TAS1R3, that fires for every sweet molecule from sucrose to saccharin; the panel scales the industry uses, relative sweetness against a sucrose standard, potency, detection thresholds, are attempts to measure what that one receptor reports, and a 2025 study showed the receptor's own response strength predicts perceived sweetness almost exactly [S-F18]. The high-intensity sweeteners of Chapter 38 are simply molecules that trip the same switch at far lower concentrations: sucralose about 600 times sweeter than sucrose by panel measure, aspartame and acesulfame-K about 200 [S-F18]. Perception is context-sensitive, temperature, acidity and concentration all bend it, which is one reason recipes cannot be reformulated by arithmetic alone [S-F1].

Why do humans want sugar at all? The question sounds naive, and for centuries nobody asked it, which is precisely the point. The anthropologist Sidney Mintz, who spent his career working in Caribbean cane country, confessed that for years he took the demand for sugar as self-evident. Then he looked at the curve: world sugar production shows the most remarkable sustained upward climb of any major food in world market history, a rise continuing across several centuries, and in five centuries it has never fallen for more than an occasional decade at a time [S36]. Even its worst collapse, when the Haitian Revolution of 1791-1803 destroyed the world's largest producer, was redressed within years [S36]. Demand like that is not an accident of taste. It was built.

The British case is the best documented. Britain consumed five times as much sugar in 1770 as in 1710, and from the 1740s to the 1820s sugar was the country's single most valuable import [S2]. The vehicle was tea. Sweetened tea spread from wealthy households to become a daily staple of the working class, and the pairing was functional as much as pleasurable: short tea breaks let labourers replenish energy quickly, and sugary tea was an affordable, accessible source of calories for people doing physically demanding work [S2]. Jam, confectionery and chocolate followed the same path down the social ladder [S2]. What looks like a simple craving was in fact a transformation of the whole diet of an industrial society, sugar supplying quick energy to people whose time and means for other food were shrinking.

Mintz's deeper claim, made in 1985 and debated since, is that sugar's history shows modern consumption, global inequality and the rise of capitalism as parts of one transformation, not separate stories [S3]. The sweetness on a London breakfast table and the labour regime of a Barbados field were two ends of one system. This book treats that as the influential interpretation it is: a lens built by

one scholar from Caribbean evidence, powerful enough to shape four decades of scholarship, and to be tested rather than assumed wherever this book uses it.

The curve kept climbing long after emancipation and long after beet broke cane's monopoly. Sugar moved from the tea cup into industrially produced food and drink, becoming what Bosma calls an ingredient listed on almost every packaged food label [S3]. By the early 2020s, the average person in Western Europe consumed about 40 kilograms of sugar and sweeteners a year, and in North America nearly 60 kilograms [S3]. If the whole world ate at the European level, global production would have to rise from about 180 million tonnes to over 300 million [S3]. The chapters that follow in this part examine where all that sugar actually goes: what it does inside food, the drinks industry it built, and the fermentation industries that turn it into everything from citric acid to antibiotics. The substitutes that now attack this empire, and the health reckoning that drives them, get their own treatment in Parts XI and XII.

One more property of the curve deserves naming now, because Part X returns to it: sugar demand has proved so durable that its failures are events. The "Dance of the Millions" of 1919-20, when the world price soared to dizzying heights and then crashed nearly to zero, ruined planters and made fortunes in a single season [S36]. A commodity that almost never declines does not become safe; it becomes a stage for speculation, and the price story of Chapter 31 begins there.

Chapter 21 - What sugar does in food

Ask why food companies use sugar and the obvious answer is the least interesting one. Sweetness is only the first of sugar's jobs. A 1985 technical review listed the functions: sweetener, preservative, texture modifier, fermentation substrate, flavouring and colouring agent, bulking agent [S28]. The food scientist's point is that sucrose is a structural material that happens to taste sweet, and removing it from a product means re-engineering the product, not just relabelling it [S29].

Start with the physics that makes all of this possible: sucrose dissolves in water to a degree few substances match. At room temperature, water will hold about twice its own weight of dissolved sugar, two kilograms of sucrose in a litre of water, and that ceiling climbs steeply with heat, reaching four parts sugar to one of water near boiling [S-F3]. A saturated sugar solution, cooled, does not simply crystallise; it becomes supersaturated, a nervous liquid holding more dissolved sugar than equilibrium allows, waiting for an excuse to give some back [S-F3]. That single property is the foundation of two very different industries. The sugar refinery exploits it to grow pure crystals on purpose, the business of Chapter 15. The confectioner exploits it to control crystallisation to the exact degree wanted: boil a syrup to concentrate it, cool it, and then either encourage fine crystals, which gives fondant and fudge their smooth, short texture, or suppress crystals entirely, which gives hard candy its glass. The candy-maker's tools for that suppression are called doctoring agents, a little acid or invert sugar or glucose syrup, foreign molecules that physically get in the way as sucrose molecules try to lock into a growing crystal [S-F3]. Every boiled sweet on earth is a lesson in managed supersaturation.

The second job is water control, and it is the oldest. Sugar binds water. In a jam jar at 60 percent sugar, so much of the water is bound up with sugar molecules that what remains cannot support microbial life; the osmotic pressure of a strong sugar solution exceeds what even the most sugar-tolerant moulds and yeasts can survive [S-F3]. This is why jams, marmalades, candied fruits and syrupy preserves exist at all: they were born from the need to preserve fresh produce before refrigeration, and sugar does the preserving, not the jar [S29]. The same chemistry works in meat curing and condensed milk, and at gentler concentrations it is why sugar is a humectant, holding moisture in a cake for days instead of letting it stale overnight [S29, S-F3]. The manufacturing consequence is hard-edged: sugar in a preserve is a safety ingredient, not a flavour one. Strip it out and the water comes back to life: the worked example in the industry's own training material, a reduced-sugar preserve, answers with chemical preservatives, pasteurisation and refrigeration [S-F21].

The third job is structure. In a cake, sugar does three quiet pieces of engineering. Creamed with fat, its crystals cut tiny air pockets into the mixture that become the cake's rise; dissolved in the batter, it delays the setting of starch, pushing the gelatinisation temperature up so that the air bubbles have time to expand before the crumb firms, which is what makes a cake light rather than dense; and in the finished product it keeps the crumb soft by holding water [S29, S-F1]. In bread, sugar feeds the yeast that makes the loaf rise; in ice cream it lowers the freezing point of the mix, so that part of the water never freezes and the product stays soft enough to scoop straight from the freezer; in confectionery syrups it raises the boiling point in proportion to concentration, which is why a thermometer can read a sugar syrup's composition directly and why the whole staircase of confectionery textures, from thread to soft ball to hard crack, exists as temperature stages [S29, S-F2]. In jam, sugar is half the gelling system: ordinary pectin only sets when sugar is abundant, which is why the sugar-free preserve in that training example abandons the system and sets its pectin with calcium instead [S29, S-F21]. Even chocolate leans on sugar structurally: a bar typically carries 20 to 50 percent sugar by weight, a 60-percent dark bar about 40, where sugar supplies bulk, viscosity and mouthfeel as much as sweetness, and confections run 15 to 50 percent sugar, with reviews of sugar-reduction methods finding 20 to 40 percent removable before texture and sweetness balance fail [C64, C65].

The fourth job is feeding microbes on purpose. At low concentrations sugar stops being a preservative and becomes the opposite: the best fermentation substrate in the kitchen. Yeast inverts sucrose to glucose and fructose and converts it to alcohol and carbon dioxide, which leavens bread, carbonates beer and turns grape juice into wine; winemakers add sugar to thin musts to raise the final alcohol, a practice old enough to carry a French name, chaptalisation; yogurt cultures work faster with a little sugar in the milk [S-F1]. One industrial version of this feeding dwarfs the kitchen and deserves its own chapter: the fermentation industries of Chapter 23, from rum to citric acid to antibiotics [S29].

The fifth job is colour and flavour under heat, and here sugar's chemistry splits in two. The golden-brown crust of bread, biscuits and roasted coffee is the Maillard reaction, a cascade between sugars and the amino acids of proteins; the deep browns and bittersweet notes of caramel are caramelisation, sugar molecules themselves breaking apart and recombining under higher heat [S29]. There is a subtlety the industry exploits: the Maillard reaction needs a reactive sugar, and sucrose is not one. Its glucose and fructose units are locked together at exactly the atoms that would react, making sucrose a non-reducing sugar; it only joins the browning chemistry after acid or heat splits it into its two monomers - most doughs and batters carry other reducing sugars that brown

unaided - which is why glucose-rich syrups brown faster than plain sucrose and why bakers choose one sugar over another for crust colour [S-F3, S-F2]. Caramelisation is the hotter pathway: sucrose begins to decompose at about 186 to 188 degrees, into hundreds of new compounds that carry both the colour and the flavour of caramel [S-F3]. And away from heat, sugar is a balancing agent, rounding the acidity of tomato sauce and ketchup, masking bitterness in cocoa and in medicine syrups, and acting as a cheap carrier that disperses colours and flavours evenly through a mix [S29, S-F1].

This functional depth explains a fact that frustrates anyone who wants sugar out of food: there is no drop-in replacement. A high-intensity sweetener replaces only the sweetness, at a few hundredths of the weight, and none of the rest, not the bulk, the gel, the rise, the scoop, the crust or the preservation [S29, S28]. The reformulation industry's own training materials lay out the whole menu of strategies, from simply removing sugar, through gradual step-downs and physically restructuring the sugar crystal, to adding sweeteners, polyols or everything at once, and every route has a price [S-F21]. Remove sugar and add nothing and you may cut barely any calories: a leading reduced-sugar breakfast cereal dropped from 37 to 25 grams of sugar per 100 grams but from 371 to only 369 kilocalories, because the other ingredients filled the space [S-F21]. Halve the sugar in a cake and replace it with high-intensity sweetener, and the lost bulk raises the calorie density of what remains, 567 kilocalories per 100 grams in the worked example against 600 after, because the flour and fat are now a larger share of a smaller cake [S-F21]. Replace sugar with polyol bulking agents and the label gains a mandatory laxative warning [S-F21]. Nestlé's heavily publicised answer, a hollowed, restructured sugar crystal that dissolves faster and so tastes sweeter per gram, launched in 2018 with the claim of 30 percent less sugar in its Milkybar Wowsomes, and delivered about 2 percent fewer calories per bar [S-F21]. The fullest answer is the kitchen sink: a sugar-free preserve on British shelves replaces sugar's six functions with about ten ingredients, water, polydextrose, maltodextrin, locust bean gum, fruit pectin, calcium chloride, potassium sorbate, sucralose, flavouring and colour standing in for what one crystalline disaccharide did alone [S-F21]. None of this makes reformulation pointless; Chapter 22 shows the drinks industry cutting sugar by a third under a single tax. But it explains why reformulation is engineering, not subtraction, and why the substitution frontier of Part XII is fought product by product, function by function, rather than won in a single breakthrough.

Chapter 22 - Drinks

The largest single industrial customer sugar ever found is the soft drink. The International Sugar Organization's consumption survey work, covering countries representing three-quarters of world consumption between 2005 and 2015, found industrial use of sugar growing nearly five times faster than direct household use, and soft-drink manufacturing use growing fastest of all, at about 4 percent a year [S30]. The can and the bottle, not the sugar bowl, became the front line of the sugar market. To see why the pairing is so tight, start with what a sweetened drink actually is: water, acid, flavour, usually carbonation, and sweetness. Nothing else on the ingredient list has a structural job. There is no starch to set, no protein to whip, no fat to cream, so the drink lives or dies on whether the sweetness arrives cleanly, carries body, and sits in balance with the acid. Sugar is ideally built for all three. It dissolves to a degree few substances match, water holding about twice its own weight of sucrose at room temperature, which lets the industry buy, ship and meter its sweetener as liquid sugar, a syrup at the edge of saturation, rather than handle crystals at the filling line [S-F3]. In the glass, dissolved sugar thickens water just enough to give a drink body, the mouthfeel that separates a cola from flavoured water; it rounds and balances the acidity that would otherwise taste thin and sharp; and it carries and releases flavour [S-F1, S-F2]. The dose is not small. Coca-Cola's Nigerian product page puts the classic recipe sold there at 10.6 grams of sugar per 100 millilitres, 35 grams in a 330-millilitre can, about seven teaspoons in a single serving [S-F28]. At that concentration sugar is doing no preservation work at all: it is nowhere near the 60 percent that protects a jam, and the can stays safe because of acidity, carbonation and, in many recipes, chemical preservatives. Sugar in a soft drink is there purely to be tasted and felt. That simplicity matters later in the story, because it makes drinks the one category where sugar can be stripped out without rebuilding the product, the exception that Chapter 36's policy history exploits and Chapter 21's reformulation paradox does not reach.

The chemistry inside the bottle is busier than the label suggests. Sweetness perception is not a fixed dial: temperature, acidity and concentration all bend it, which is why a flat warm cola tastes cloying and the same drink cold and fizzy tastes balanced, and why recipes cannot be reformulated by arithmetic alone [S-F1]. And the sugar itself does not hold still. Colas run at about pH 3.5, acidic enough to hydrolyse sucrose into free glucose and fructose within weeks of bottling, so a sucrose-sweetened cola delivers something chemically close to the high-fructose corn syrup version long before anyone drinks it [S-F24]. The inversion even has an old name in the trade: the sugar has "inverted," the same chemistry the confectioner triggers on purpose with acid or enzyme. There is a second, stranger loop between sugar and soft drinks: the acid that balances the

sweetness is itself usually made from sugar. Citric acid, the industry's standard acidulant for colas and lemonades, has been grown in fermentation vats fed on sucrose or molasses since the 1920s, and the company that pioneered the process, Pfizer, built its early fortune supplying it to Coca-Cola, Pepsi-Cola and Dr Pepper [S40]. Chapter 23 tells that story; here it is enough to note that even the sour half of a sweet drink usually starts life in a sugar solution.

The industry that made this market was assembled in the late nineteenth century, when carbonated water met the soda fountain and cheap refined sugar. The landmark date belongs to Atlanta: on 8 May 1886 a pharmacist named John Pemberton took a new syrup to Jacobs' Pharmacy, where it was sold at the soda fountain as Coca-Cola; the company records sales of nine drinks a day for that first year [S-F30]. The franchised bottling system that followed turned a fountain syrup into a product that could reach anywhere rail and roads reached, and every bottle carried sugar's freight. Sweetened tea and coffee had made sugar a daily habit a century earlier (Chapter 20); the bottling line industrialised the habit, and the twentieth-century cola wars were fought, at bottom, over who got to dissolve sugar in the public's water.

The drink industry also shows how quickly sugar's hold can break when price allows a substitute. In the United States, the world price shock of 1974 made sucrose suddenly expensive, and high-fructose corn syrup, made from maize by enzyme technology (Chapter 38), was waiting. The endgame is documented in the business press of the day: in November 1984 Pepsi-Cola raised high-fructose corn syrup to 100 percent of the sweetener in brand Pepsi and Pepsi Free, up from approval levels of 50 percent in bottles and cans since April 1983 and 80 percent in fountain syrup since September 1983, and Coca-Cola moved to 100 percent corn syrup in bottled and canned Coke, its fountain syrup having gone fully to corn syrup that May [C94]. The displacement was total, fast and openly price-driven: in the American soft drink, sucrose lost its biggest customer within a decade. It could happen there and not elsewhere because the economics were political: American sugar import barriers kept sucrose dear and American maize policy kept corn cheap, an advantage no other large market reproduced, which is why the same global brands are made with different sweeteners in different countries to this day [C28]. It could happen at all because of what a drink is: with no structure to rebuild, swapping one syrup for another was a purchasing decision, not a product redesign.

The twenty-first century brought pressure from the other direction, and here drinks became the proving ground for the reformulation that food cannot manage. Sugar-sweetened beverage taxes now operate across most of the world, at least 108 countries as of 2022 by the WHO's count [S16]. The evidence that they change what is made, not just what is bought, is clearest in Britain, where

the Soft Drinks Industry Levy of 2018, tiered by sugar content, pushed manufacturers to reformulate: within a year the share of levy-liable drinks above the higher sugar threshold had fallen by a third, and total sugar sold in soft drinks dropped by about 34 percent, against 3.5 percent under a voluntary programme running in parallel [C29, C30]. The most studied of the early national taxes, Mexico's 2014 excise tax of one peso per litre, cut household purchases of taxed drinks by about 6 percent in its first year against the pre-tax trend, the decline deepening to 12 percent by December and largest in the poorest households, while purchases of untaxed drinks, mostly bottled water, rose [C131]. Chapter 36 weighs the health evidence and the policy design; the point for this chapter is industrial. Reformulation in drinks is a procurement and flavour-balancing exercise, not the ten-ingredient rebuild of Chapter 21's sugar-free preserve, so a tax tier is a problem a drinks company can engineer its way under in a single product cycle. The industry that made sugar's biggest market also turned out to be the industry that could unmake it fastest.

One corner of the aisle still buys sugar for its original virtue, as fuel. Sports drinks are engineered sugar solutions: the exercise-science guidance of the 1990s, formalised in the American College of Sports Medicine's 1996 position stand, prescribed drinks of 4 to 8 percent carbohydrate, glucose or sucrose, with a little sodium, delivering 30 to 60 grams of carbohydrate an hour to sustain work past the hour mark without slowing the stomach's emptying [S-F29]. Energy drinks and bottled teas have added new channels on the hedonic side, and tea and coffee, sugar's first mass vehicles (Chapter 20), continue to carry sucrose across Asia in volumes the soft-drink trade can only envy. Through all of this the industry's scale kept growing, and its structure was set early: wherever people drink sweetness, sugar's market follows, and the fight over that market, between cane, corn and chemistry, is one of the central commercial contests of our time.

Chapter 23 - Fermentation and industry

Long before it fed soft-drink lines, sugar fed vats. Alcoholic fermentation, yeast converting sugar to ethanol and carbon dioxide, is the oldest biotechnology, and every tradition of wine, beer, mead and cider runs on the sugars of grapes, grains, honey and fruit [S29]. Cane sugar's own fermentation empire begins with molasses, the dark residue of crystallisation, and its most famous product is rum, the distilled spirit of the sugar islands, an industry Chapter 24 takes up with the byproduct trades. The deeper story of this chapter is what happened when industrial chemistry learned what brewers and bakers had always known: that sugar is the best feed a microbe can get.

The reasons are practical. Refined sugar and molasses arrive pure, concentrated and predictable, a defined carbon source that needs no digestion before use, stores without spoiling, and dissolves cleanly into a fermentation broth. Yeast even carries the key for sucrose in particular: it secretes invertase, splitting the disaccharide into glucose and fructose before burning either [S-F1]. The craft is in the feeding, and the industry that makes the feeding plainest is the one that grows yeast itself. Baker's yeast is farmed in tanks on molasses, and the whole art of the process is a paradox: the grower wants the yeast to breathe, not ferment. Fermenting sugar into alcohol yields little new yeast; respiring it with abundant air yields the most biomass per gram of sugar. So the tanks are run fed-batch, the molasses trickled in at a rate that holds the culture just below the point where it tips into alcohol production, with air blown through the broth, and the culture escalated through four or five stages from a flask to fermenters of 100 to 150 cubic metres [S-F27]. Every packet of baker's yeast is the product of sugar rationed out with precision, which is a fitting emblem for the whole sector: industrial fermentation is sugar metering, at tank scale.

The landmark case of sugar feeding heavy chemistry is citric acid. The acid was once squeezed from fruit, imported as unripe citrus and citrate of lime from Italy, California and the West Indies, and its biggest customer was the new soft-drink industry, which used it to preserve and sharpen colas and lemonades; the Brooklyn firm of Pfizer, founded by two German cousins in 1849, dominated that trade from the 1880s [S40]. The science that broke the fruit trade was old, the botanist Carl Wehmer had shown in 1893 that a mould could make citric acid from sugar, but nobody could run it at commercial scale until James Currie, a food chemist, joined Pfizer in 1917 and took on Aspergillus niger, an air-hungry mould that converts sugar to citric acid only at a thin, well-aired surface [S40]. Currie's answer was shallow pans, controlled humidity and patient tuning; Pfizer's pilot plant of 1919 ran under a name that said exactly what it did, SUCIAC, "Sugar Under Conversion to Citric Acid" [S40]. Yields climbed until a full SUCIAC plant opened in 1926, and that year fermented citric acid

outproduced the citrus-based kind; by 1929 Pfizer made 5.9 million pounds of the acid without using a single lemon or lime [S40]. In 1933 Currie's assistant Jasper Kane substituted molasses, the cheap residue of the sugar refinery, for refined sugar as the feed, closing the loop: the soft drink's sourness now came from the same sugar economy as its sweetness [S40].

The deeper consequence was technological. Pfizer never got citric acid to run in deep stirred tanks, but in 1929 it did get gluconic acid, a food and cleaning chemical, to grow submerged in aerated, pH-controlled deep tanks, and in 1936 it began selling vitamin C made with submerged fermentation as the first step [S40]. When the British and American governments went looking in 1941 for anyone who could mass-produce penicillin, a mould product that laboratory flasks could barely yield, it was Kane who proposed in 1942 that the deep tanks built for sugar-fed fermentations take the job [S40]. Pfizer bought an old Brooklyn ice plant for its refrigeration machinery and on 1 March 1944 opened the world's first large-scale penicillin factory: fourteen 7,500-gallon tanks, fed on corn steep liquor, milk sugar, salts and minerals, running around the clock and soon producing five times what had been estimated [S40]. Most of the penicillin that went ashore with Allied forces on D-Day came from that plant [S40]. The chain of consequence runs straight from the sugar economy to the antibiotic era: the engineering that made penicillin a bulk product, sterile air, submerged aerated culture, fed tanks, was paid for and perfected on sucrose and molasses.

The modern fermentation industry runs on the same template, at continental scale. Five bulk chemicals are grown in vats from sugar feedstocks, usually corn glucose but also cane molasses and cassava: citric acid from Aspergillus niger, lysine and monosodium glutamate from Corynebacterium glutamicum, xanthan gum from Xanthomonas campestris, and vitamin C [C67]. On the cane side, one modelled molasses-to-lysine process achieved 0.31 grams of lysine per gram of glucose at a 26.5 percent return on investment [C68], and molasses remains a working feedstock for baker's yeast, citric acid, amino acids, vitamins and lactic acid [S-M23]. This industry has two signatures worth recording. The first is concentration. Fermentation economics are capital-hungry, energy-hungry and margin-thin, and they migrated to China from the 1990s: on Downey's practitioner estimates, China now makes about 62 percent of world output across these five markets, dominating citric acid from plants clustered in Shandong at roughly 3 million tonnes a year, holding more than 60 percent of world lysine, the largest share of the 350,000-to-450,000-tonne xanthan market, and overwhelmingly producing vitamin C, with the same handful of firms, Fufeng and Meihua among them, running several products off the same corn stream [C67]. The second signature is a criminal record. These products are chemically identical whoever makes them, they are sold by a few producers to a

few large buyers, and no public price exists anywhere: there is no futures market, only assessed prices and annual contracts, so the only way to learn a competitor's price is to ask them, and asking is the crime [C67]. The record, as Downey's survey assembles it, is as dense as the logic predicts. In 1996 Archer Daniels Midland pleaded guilty and paid a 100-million-dollar criminal fine, then the largest criminal antitrust fine ever, for its role in two international conspiracies fixing prices and allocating sales in lysine and citric acid, markets then worth 600 million and 1.2 billion dollars a year respectively [C67b]. The case had begun in 1992 when an ADM executive, Mark Whitacre, told the FBI about the lysine conspiracy and spent nearly three years secretly taping the meetings; the recordings caught the company philosophy in one sentence, "the competitor is our friend and the customer is our enemy," and three executives went to prison, while Whitacre himself, who had been embezzling throughout, served a longer sentence than the men he exposed [C67]. Vitamin C produced something stranger: American buyers sued four Chinese producers for fixing export prices, the producers answered that Chinese law required them to do it, and the dispute ran to the US Supreme Court, which ruled unanimously in 2018 that American courts must respectfully consider, but are not bound by, a foreign government's reading of its own law [C67]. A fight over the price of a vitamin ended up writing the rule for how American courts read foreign statutes.

Sugar also enters manufacturing without being fermented at all. The pharmaceutical industry buys pharmacopoeia-grade sucrose as an excipient, an inactive but working ingredient: filler and binder in tablets and granules, body in powders and lozenges, coating material for pills and pastilles, sweetness and viscosity in cough syrups and drinkable ampoules, and, everywhere, taste-masking, since many active drugs are aggressively bitter [C66]. Sugar appears in cosmetics, and its chemistry, a small, cheap, water-loving molecule with reactive handles, makes it a building block for surfactants and polymers, markets the biorefinery vision of Chapter 40 wants to expand [S28]. The volumes are modest beside food and fuel, but they mark sugar's reach: few bulk commodities touch both a child's breakfast and a course of antibiotics.

The largest fermentation market of all is fuel ethanol, and it is large enough to deserve its own chapter. Chapter 25 tells how Brazil turned sugar into a national fuel system, and how that choice now shapes the world sugar price itself.

PART VIII - THE BYPRODUCT INDUSTRIES

Chapter 24 - Molasses

Every crystallisation leaves something behind. When sucrose comes out of the boiled syrup as crystals, the uncrystallisable remainder is molasses: a dark, dense syrup holding the sugars that would not crystallise, the plant's minerals, and the process's impurities [S29]. It is the industry's original byproduct, and for three centuries it has been an industry of its own. The reason is composition: molasses is still mostly fermentable sugar, and anything fermentable is a feedstock [S-M23].

The oldest molasses industry is rum. The sugar islands distilled their residue into spirit almost as early as they made sugar, and rum became a trade good in its own right, woven into the same Atlantic commerce as the crystals: the triangular trade carried molasses and rum from the Caribbean to New England and Europe as one leg of the circuit that carried enslaved Africans from Africa and manufactures from Europe [S2b]. New England made itself a distillery power on that leg: by about 1770 the mainland colonies ran roughly 159 rum distilleries, 63 of them in Massachusetts, converting some six million gallons of molasses a year, with Medford rum a byword for quality [E44]. Today the global rum industry is worth about 16 billion US dollars, still concentrated in the Caribbean and Asia-Pacific, and still fed principally on cane molasses [C35]; one industry writer reports from well-placed sources that molasses can run to as much as 80 percent of a distillery's production cost [C36]. That dependency now runs in a surprising direction: modern sugar factories extract so completely that they leave less sugar in their molasses, and Caribbean distillers increasingly import higher-test material, with even Guyana, once a molasses supplier, becoming an importer [C36].

Rum itself divides on the feedstock line. Most rum is distilled from molasses: blackstrap, the final molasses after repeated boiling and crystallisation, is the standard fermentation medium for its abundance and low cost [C35]. The French tradition draws the other line in law: rhum agricole is defined as a spirit distilled exclusively from fermented cane juice, with an aromatic content of at least 225 grams per hectolitre of pure alcohol [C35]. Ageing law maps the trade's geography: Australia, the Dominican Republic and Panama all require at least two years before a spirit may be sold as rum, while Mexico asks only eight months [C35]. And the industry's own technical literature names its standing headache, which is not supply but consistency: minimising the variability of feedstock quality, running fermentations to completion, preventing microbial contamination, and keeping yeast strains performing batch after batch [C35].

The second great use is invisible: animal feed. Molasses goes into feed rations across the world, valued for energy and palatability, often sprayed onto other

feedstuffs - the molassed beet pulp of Chapter 17 is one - and in its blackstrap form it also sells as a food and dietary supplement [S2b, C34]. The third is industrial fermentation (Chapter 23): yeast production, citric acid, vitamins, amino and lactic acids, and ethanol [S-M23, C34]. But molasses is the fermentation industry's fallback, not its favourite: in Europe the industry runs on starch and glucose for half its feedstock, sugar and thick juices for nearly a third, and molasses for only about a fifth, with beet molasses substitutable at the margin according to price, which is why the European Union's molasses imports, 95 percent of them cane, halved over the decade to 2016 without any shortage appearing [C34]. That account comes from the European beet growers' association arguing against the fermentation industry's claim of scarcity; the tonnages are Eurostat's, the interpretation is the lobby's, and the two should not be confused [C34]. The International Sugar Organization's recent framing captures the shift: molasses is moving "from residual by-product to strategic feedstock," with research pipelines toward sustainable aviation fuel, bio-based chemicals and bioplastics [C33]. Even the sugar still locked inside it is mined: in the beet industry, modern chromatographic desugarisation recovers over 80 percent of the sucrose remaining in molasses, a technology Chapter 16 traces from the Steffen house to the simulated moving bed [C113].

Molasses has one structural trait that shapes all these trades: it is expensive to ship relative to its value, so most of it is consumed near where it is made [C34]. This is why distilleries and feedlots cluster near sugar factories, why the molasses trade is regional rather than global, and why disruptions to molasses supply hit rum producers so hard. The byproduct industries of sugar are local industries chained to the mill, a pattern Chapter 26 completes with bagasse.

Chapter 25 - Ethanol

Sugar's largest non-food career is fuel. Ethanol made from cane or beet can be blended into petrol, and one country built a national strategy on that chemistry: Brazil. The programme, Proalcool, was launched in 1975, after the 1973 oil crisis made Brazil's dependence on imported fuel a strategic vulnerability [S32, S33]. Its roots ran deeper, to 1930s experiments with alcohol fuel, but the 1975 decision made it a system: guaranteed prices, credit lines, and a state research programme, Planalsucar, breeding cane for fuel as much as for sugar [S32, S33].

The results were enormous and uneven. Through the 1980s Brazil ran the world's first mass market for ethanol cars, then stumbled when oil prices fell and sugar prices rose; the 1990s brought decline and deregulation [S32]. The revival came from engineering: the flex-fuel car, introduced in the 2000s, could run on petrol, on hydrous ethanol, or on any blend of the two sold at Brazilian pumps, putting the fuel choice in the driver's hands at every filling station [S32]. From that point the Brazilian mill became a dual factory, and this is the fact that now shapes the world sugar market: Brazilian mills routinely swing their output between sugar and ethanol as relative prices move. In 2013/14 the mix ran about 48 percent sugar to 52 percent ethanol, and the swing range in industry discussion runs from 60/40 to 40/60 either way [C39]. The mechanism is simple: the mill flexes by extracting less sucrose from the juice, leaving more sugar in the molasses stream for the fermenters [C39]. The swing bites hard: a shift to ethanol in 2018/19 cut Brazil's sugar output by 9 million tonnes to a 12-year low, and Biosev, then the country's second-largest cane processor, invested in distillation columns giving two of its mills the option of running 90 percent of their cane to ethanol, up from 50 [C38]. Seven milling groups controlled about 55 percent of Brazil's cane processing as of the mid-2010s [C39]. The swing is visible in the official record: between the USDA's November 2025 and May 2026 editions, the expected Brazilian cane mix moved from a forecast 51 percent sugar to a forecast 52 percent ethanol, after Brazil raised the anhydrous ethanol blend in gasoline from 27 to 30 percent in August 2025 [C47, C92].

The sugar-ethanol link is a two-way valve. When oil is dear, cane goes to fuel and world sugar supply tightens; when sugar is dear, the flow reverses [S22]. Other countries have built on the model at smaller scale, with India's ethanol blending programme, targeting 20 percent nationally, now diverting millions of tonnes of sugar equivalent and altering the world balance (Chapter 32) [S22, C42, C43].

Ethanol's environmental accounting is genuinely contested, and the book will not flatten it. Proalcool's history includes real environmental costs, notably vinasse pollution of waterways, and real labour strife [S32]. The greenhouse

case for cane ethanol depends on land-use assumptions that researchers argue over; what is documented is the engineering achievement itself: a tropical crop powering a national vehicle fleet, with the factory burning its own fibre (Chapter 26) to run the process [S32]. Second-generation ethanol, made from bagasse and straw rather than juice, has been the industry's promised next act for twenty years, and its history so far is a study in the distance between a plant's nameplate and its output. The first commercial-scale plants arrived between 2011 and 2020: Crescentino in Italy, Project Liberty and DuPont's Nevada plant in Iowa, GranBio's BioFlex in Alagoas, Raizen's Costa Pinto in Sao Paulo, Clariant's Podari in Romania. Most are gone or converted, each for its own reason: Crescentino died with its parent company's 2017 bankruptcy [C121]; Project Liberty paused in 2019, its owners blaming federal waiver policy that gutted the mandated market [C122]; DuPont's plant was sold in 2018 and converted to biomethane [C120]; Podari was repurposed after economic losses [S24]; Costa Pinto, opened in 2015, was retired to research duty in April 2025 [C116]. The output figures explain the strain: total American cellulosic ethanol production in 2022 ran to about 1.4 million gallons, roughly five percent of a single Iowa plant's nameplate [S24].

The verified picture as of the 2024/25 season centres on Brazil, and even there the numbers are humbling. Raizen's first unit ran from 2015 to its research-duty retirement, and in October 2023 the company inaugurated a plant at Bonfim with a nameplate of 82 million litres a year, with more under construction [C116, C117]. Yet the company's own earnings release records total second-generation output across all its units of 49.7 million litres in the nine months from April to December 2024, the first ramp-up year of the new plant [C116]. GranBio's BioFlex, a 265-million-dollar build in Alagoas, has been suspended since the 2021/22 harvest according to trade press, while the company's own audited statements of mid-2025 still describe it as the largest second-generation plant in operation in the world; a 1.5-billion-real redesign into a multi-product biorefinery was announced in January 2025 [C118, C119]. The demand side is made by policy: Raizen has pre-sold its first five plants' fifteen-year output, 4.3 billion litres, mostly to Shell, against European mandates requiring non-crop biofuels, and reported a 14 percent contribution margin on second-generation ethanol in an August 2024 presentation [C117, C123]. Without those mandates and contracts, the fuel would have to beat first-generation ethanol at the pump on cost alone. On the cost side, the review literature reports enzyme costs down from about two dollars to about thirty cents per gallon over a decade, its own figure hedged, while pretreatment of the fibre remains the most complex and costly stage [S24]. And there is a trade the sugar factory itself must make: bagasse diverted to a cellulosic plant is bagasse the mill's boilers do not burn, so

the newest use of the fibre competes with the oldest, the mill's own power (Chapter 26). Chapter 40 assesses where the technology goes from here.

Chapter 26 - Bagasse and the rest

For every tonne of sugar a factory makes, it produces several tonnes of other things, and what a society does with them says much about its industrial maturity. The industry's own training text puts the balance in its simplest form: from 100 kilograms of cane, about 10 of sugar, 30 of bagasse, 5 of final molasses and 4 of press mud [S41]. These are teaching-example magnitudes, not universal constants - variety, climate and mill practice move every figure - but they fix the proportions. Molasses has Chapter 24. This chapter is about the fibre and the mud, and about a material whose every use is decided by four physical facts: it is wet, it is perishable, it is bulky, and it arrives in a season.

The bagasse itself needs explaining, because the mass balance hides an oddity. In textbook milling examples, a hundred tonnes of cane yields roughly thirty tonnes of bagasse and 105 to 110 tonnes of mixed juice - more liquid than the cane itself, because the mill sprays imbibition water into the mill stream to wash sugar off the fibre, forty tonnes of it to the hundred of cane in the text's worked example; the "extra" tonnes are added water, not created matter [S41]. That juice runs 12.5 to 15 degrees Brix at 80 to 85 percent purity, so the hundred tonnes of cane carries in roughly 11.5 to 14 tonnes of sucrose; what leaves as saleable crystal is less again, since molasses, filter mud and process losses each take a share before the pan ever boils [S41]. What is left in the fibre matters for everything that follows. Milling is set to expel bagasse at about 50 percent moisture, the condition the boilers want [S-M26], and enough residual sugar clings to fibre and pith alike to feed anything that grows [S-M35].

The fibre's first destiny is the boiler: burning bagasse powers the factory itself, the closed loop of Chapter 17 [S2b, S-M16]. Everything else bagasse can become is a claim on what the boiler does not need, which is why the energy story and this one are coupled. The Mauritian export-power programme's stated design was to raise the efficiency of generation and of power use inside the factories precisely so that a bagasse surplus would exist to sell [S-M17]. Every tonne of steam economy is a tonne of fibre freed for something else.

That something else must reckon with the material's nature. Cane crushing runs three to eleven months of the year depending on country, but a pulp mill or board plant wants fibre all year, so bagasse must be stored for six or seven months - and stored bagasse is alive [S-M35]. The residual sugars ferment within days, microbes multiply through a temperature succession - yeasts and fungi first, mesophiles above 22 degrees, thermophiles from about 40, lactic-acid bacilli at 50 degrees Celsius - and the pile heats itself; cellulose attack begins above 30 degrees, and the pile's pH decides whether its chemistry preserves the fibre or eats it [S-M35]. The review's practice accounting is not

gentle: fermentation loss alone runs 5 to 6 percent, and a total fibre loss of 10 percent in storage counted as good practice, 15 percent as acceptable [S-M35]. Depithing does not remove the problem, because the nutrients ride on fibre and pith alike [S-M35]. Dry the fibre instead and the fire hazard becomes, in the review's words, extremely great; the same catalogue of selection factors includes the danger of lung disease among handlers and the cost of insurance [S-M35]. And the stuff is bulky: its low density forces baling or dense stacking merely to keep the storage area and the handling within bounds [S-M35].

A whole storage engineering grew up around those facts in the decades when bagasse pulp mills spread, and a 1983 technical review catalogues its families [S-M35]. Bale storage was the oldest: the Celotex system, in wide use for over 45 years, stacked bales under metal roofs with air passages for cooling; Louisiana's Thibodaux system mechanised bale handling end to end with 125-kilogram bales; Taiwan's used small 25-to-30-kilogram bales where labour was cheap; and the large-bale variant pressed 800-kilogram bales of moist depithed fibre right at the sugar mill, cutting losses and handling costs, and serving pulp mills more than 100 kilometres away, as at Sancristobal in Mexico [S-M35]. Dry bulk storage went further: Venezuela's Tablopan system depithed completely, refined and dried the fibre to 90 percent dryness and pressed 200-kilogram mats, while a Jamaican building-products plant briquetted and pelletised to 300 to 400 kilograms per cubic metre - answers that cost fuel, and the review notes drying is a costly process where energy is purchased dear [S-M35]. Wet bulk storage took the opposite path: the Ritter process impregnated the fibre with a molasses-seeded biological liquor and flooded it into piles, where acid, anaerobic conditions at pH 1.5 to 4 held fibre losses to the minimum and fire hazard to almost nothing, at the price of stainless-steel equipment, high-BOD effluent unless the water is recirculated, and heavy water and power use; the largest Ritter store of its day opened at the Ngoye paper mill in Zululand in 1956 [S-M35]. The review even records a disagreement among practitioners: Taiwan Sugar's technologists held that stored bagasse pulps better and with less chemical, while the industry's Dr Cusi insisted fresh undegraded bagasse gives the stronger pulp and higher yield - a dispute over whether "aged" fibre is genuinely improved or merely coped with [S-M35].

The uses that justify all this handling concentrate in one proven chain. Paper and paperboard are the oldest non-fuel use and the one with the deepest documented industrial record. Tamil Nadu Newsprint and Papers in southern India, whose single largest fibre is bagasse, ran a paper capacity of 440,000 tonnes a year plus 200,000 tonnes of paperboard in fiscal 2024, with bagasse at 50 to 60 percent of its printing-and-writing furnish against about 30 percent wood pulp, and its board plant at 98 percent utilisation [C129]. The fuel-versus-fibre tension is solved there as a priced trade: the company barters coal and

steam to local sugar mills in exchange for their bagasse, topping up on the open market, and powers itself from a 103.62-megawatt captive plant, with 35.5 megawatts of wind on top [C129]. The barter is the point. Bagasse always has a fuel value, so a fibre user must outbid the boiler, and the cleanest way to do it is to hand the mill the coal its boilers would otherwise have replaced. Beyond paper, the industry's use-lists keep lengthening - reconstituted panel board, agricultural mulch, charcoal, activated carbon, furfural and dietary fibre all appear [S2b, S41] - but the lists run longer than the working examples, and outside the paper chain full-scale bagasse industries remain the exception. The newest claimant is second-generation ethanol, fuel made from fibre rather than juice: every tonne of bagasse a cellulosic plant takes is a tonne the boilers do not burn, so the newest use trades directly against the oldest, and the first commercial plants have run far below their nameplates, as Chapter 25 recounts [S24, C116].

The rest of the balance sheet is smaller but real. Filter cake, the pressed-out mud from clarification - about 4 kilograms per 100 of cane in the textbook balance [S41] - goes back to the fields as fertiliser and soil amendment, yields sugarcane wax, and in newer practice feeds biogas plants [S2b, S41]. Beet factories have their own versions: pulp pressed and dried into animal feed, whose three commercial routes Chapter 17 walks through [C100]; carbonation-lime residue at about 80 percent calcium carbonate returned to improve agricultural land; and concentrated molasses solids from desugarisation sold to the feed industry [S-M27]. Vinasse, the liquid residue of ethanol distillation, is the dark side of the ledger. Returned to fields it is valuable, and its use is agronomy, not disposal: in Brazil, fertirrigation is its primary destination, with the applied potassium dose determined weekly against the crop's own extraction of about 185 kilograms of K2O per hectare, and Sao Paulo state regulates the application by technical norm [C108, C109]. Discharged carelessly it poisons waterways, and its mismanagement stains the environmental record of Brazil's ethanol programme (Chapter 37) [S32].

The modern ambition is the biorefinery: a factory that sells sugar, ethanol, electricity, chemicals and materials from the same cane, wasting nothing. The pieces all exist in operating form somewhere - Kakira in Uganda runs sugar, bagasse power, ethanol and spirits as one integrated complex [S15] - but assembling them profitably at scale is the industry's unfinished project, and the reason is written in this chapter's arithmetic: every new use bids for the same thirty tonnes of seasonal, perishable fibre, against a boiler that needs it, a pulp mill that must store it, and a fermenter that must beat both prices. Chapter 40 gives the ambition a hard look.

PART IX - THE BUSINESS

Chapter 27 - Producers and millers

Who makes the world's sugar? The structure is paradoxical: a commodity produced in over a hundred countries whose export supply concentrates in a handful. Brazil stands alone at the top, projected to supply about 23 percent of world sugar output in 2033, with India near 19 percent, Thailand the other major exporter, and the European Union leading the beet world [S22, C2]. The company layer beneath these countries mixes every ownership form capitalism has invented: family groups, cooperatives, listed multinationals and state legacies.

Brazil's industry runs through large milling groups, seven of which controlled about 55 percent of the country's cane processing by the mid-2010s, led by Copersucar, a growers' cooperative pool, and Raizen, the Shell-Cosan joint venture, which counted 24 mills in that mid-2010s snapshot [C39]. Consolidation continued: in February 2021 Raizen agreed to absorb Louis Dreyfus's Biosev arm, nine production units and up to 32 million tonnes of cane-crushing capacity, for R$3.6 billion plus equity, taking the combined group to about 17 percent of Brazil's centre-south crop on a 2019/20 basis [C54, C55]. Thailand's structure is the opposite pole: around 107,000 smallholders growing for contract mills that own no cane, under state milling licenses and production quotas [E26]. Australia's industry was dominated for a century by CSR, whose seven Queensland mills and three refineries passed to Singapore's Wilmar International in 2010 for an enterprise value of 1.75 billion Australian dollars [C21]. Europe's beet processing concentrates in a few majors: Sudzucker; Tereos, a cooperative of 15,800 French grower-members that processed 21.1 million tonnes of cane in its 2023/24 Brazilian campaign, making 1.9 million tonnes of sugar and, by its own annual report, ranking as Brazil's second-largest producer alongside its European beet core [C59]; Nordzucker, whose 2025/26 figures, 2.8 million tonnes of beet sugar plus 0.6 of cane from its Australian arm on 2.34 billion euros of revenue, came with a 226-million-euro operating loss, including some 160 million of non-recurring charges in Europe, a concrete picture of post-quota, low-price pressure on European beet [C59, C72]. The cooperative form runs strong in beet: France's Cristal Union is 9,000 grower-members farming 45 percent of the country's beet area, and the American beet sector now runs substantially on grower cooperatives: Amalgamated Sugar, by its own account the country's second-largest beet-sugar manufacturer, is a cooperative of more than 700 grower-members, Western Sugar is a growers' cooperative of similar size, and Michigan Sugar, by its own account the third-largest beet processor, sells under its century-old Pioneer brand [C95, C96, C97].

India, the other pole of world production, mills its cane through hundreds of factories under state-set prices. The national government fixes a Fair and Remunerative Price for cane each season: 3,550 rupees per tonne (about 41.7 US dollars) for 2025/26, up 4 percent on the year, and Uttar Pradesh, Uttarakhand, Haryana and Punjab layer State Advised Prices on top, untied to sugar recovery and typically higher [C126]. The sugar floor, by contrast, has not moved: the minimum sale price for sugar has stood at 31,000 rupees per tonne (about 364 dollars) since 2019, even as cane prices climbed [C126]. The strain lands on the miller, and then on the farmer: a 2026 US agricultural attache report, citing industry sources, put the season's cane dues at 8.87 billion dollars, of which mills had paid 80 percent, leaving 1.79 billion in arrears concentrated in Karnataka and Maharashtra [C126]. The sector's scale keeps growing through the strain: 541 mills crushed in 2025/26 against 493 the year before, and the Indian Sugar and Bio-Energy Manufacturers Association's April 2026 production estimate of 27.2 million tonnes came in 12 percent below its initial forecast after excessive monsoon rain cut cane across Maharashtra, Uttar Pradesh and Karnataka [C126].

Brazilian cane, by contrast, trades on a formula rather than a fixed price. Since 1999 the Consecana-SP model, run jointly by the millers' association Unica and the growers' federation Orplana, has priced Sao Paulo cane off its total recoverable sugar against the value of what the mill sells, with the Cepea institute publishing the reference: 1.0816 reais per kilogram of recoverable sugar, roughly 149 reais per tonne of cane, through March 2026 [C127]. The model's own rules call for five-yearly reviews, but none had landed in over five years; monthly price circulars froze through 2024 and 2025 while the two sides argued, until an April 2026 memorandum committed them to an update [C127].

Two things distinguish sugar's producers from other farm industries. The first is integration: the mill sits at the centre, and the grower, whether estate, smallholder or cooperative member, is bound to it by the crop's perishability (Chapter 12). The second is the byproduct economy: the modern producer sells sugar, ethanol and electricity from the same plant (Chapters 25, 26), so "sugar company" increasingly means energy company that also sells sweetness. Chapter 28 follows the sugar onward to the refiners, where a different set of names takes over.

Chapter 28 - Refiners

Refining, the conversion of raw brown crystals into white sugar (Chapter 16), built sugar's most famous business dynasties and its sharpest monopoly fights. The American story is the extreme case. The American Sugar Refining Company, built by Henry Osborne Havemeyer, known in his day as the Sugar Pope, controlled roughly 98 percent of United States refining by 1891 after absorbing four Philadelphia refineries [C19, C20]. The federal government's Sherman Act case against it failed in 1895, when the Supreme Court held in United States v. E. C. Knight that a monopoly of manufacture was not a monopoly of interstate commerce, a ruling that narrowed early American antitrust law for a generation [C19]. The economist Frank Taussig, watching it happen, argued the trust was made by policy as much as by business: the tariff's differential between raw and refined sugar sheltered refining margins, and Havemeyer himself called the customs tariff bill the mother of all trusts [E30]. The economics ran the way Taussig described: price wars, against Spreckels in 1889-92 and Arbuckle in 1897, burned the margin the tariff protected, and consolidation followed, seventeen of the country's twenty-three refineries inside the combination by the end of 1887 [E30, E37]. In Britain the dynasty was doubled: Henry Tate's Thames Refinery opened in 1878 specialising in cube sugar, Abram Lyle's Plaistow Wharf refinery followed in 1882 producing the Golden Syrup still sold today, and their 1921 merger created a firm then refining about half the country's sugar [C16]. As late as 1878 Britain had 74 refineries; the story of the following century is fragmentation becoming duopoly [E6].

The modern map shows refining's two surviving logics. The first is port refining: import raw sugar by bulk vessel, refine it near the consumer. The extreme proof is Al Khaleej Sugar at Jebel Ali in Dubai, producing since 1995, expanded in 2016 to a capacity of 7,000 tonnes a day from Brazilian, Indian, Australian and Thai raws, exporting to more than fifty countries and supplying, by its own account, about 3 percent of global refined sugar output, a world-scale refinery in a country that grows no cane at all [C22]. The second is integration: cane-country refiners like Florida Crystals, which began farming in Florida in 1960, moved into refining in the late 1990s, and assembled today's ASR Group by acquiring Domino in 2001, C&H in 2005, Redpath in 2007 and Tate & Lyle's European sugars business in 2010, the purchase that ended Tate & Lyle's own 130 years in sugar refining and turned it into a speciality ingredients company [C18, C16, C17].

The modern map fills in around those two logics. In the Gulf, Saudi Arabia's United Sugar Company runs about 1.2 to 1.3 million tonnes of capacity at Jeddah with an expansion toward 1.7 million launched in 2014, and Oman Sugar Refinery at Sohar Port adds a further million tonnes with half a million

tonnes of bulk raw storage [C82, C83, C86]. Egypt's Canal Sugar project at West Minya, a billion-dollar agro-industrial build with Al Khaleej participation, presents itself as the world's largest beet sugar plant at up to 750,000 tonnes a year [C87]. London's Thames Refinery, Havemeyer-era Tate's heir, still runs at 1.2 million tonnes a year under ASR Group [C91]. Two Asian systems show the state shaping the sector outright. Japan imports about a million tonnes of raws a year into eleven refineries; the government buys the raws from the refiners at world price and sells them back at a higher stable price, holding the domestic price near 2,000 dollars a tonne and the refining margin positive, with the surplus redistributed to domestic growers, and the sector has consolidated into two majors [C75]. Indonesia runs the mirror image: eleven dedicated refineries with 5.02 million tonnes of capacity, fed by state-rationed raw-import permits, running at about 70 percent utilisation in 2025/26, forbidden by regulation from making anything but refined sugar for the food industry [C76]. South Korea's market, about 1.2 million tonnes a year, is served by three domestic refiners, CJ CheilJedang with 47 percent of the domestic refined market in 2022, Samyang Corporation with 32 percent and TS DaehanJedang with 21 [C81]. Inside the refinery itself the business is a yield game: white recovery from raws runs 95 to 98 percent depending on raw quality and design, molasses the main loss, energy met by cogeneration [C79].

Refining remains politically charged. The United States government's 2021 case to block US Sugar's acquisition of Imperial Sugar, argued on concentration grounds within the refining sector, shows the Havemeyer problem is alive in the twenty-first century [S31]. The white premium of Chapter 30 is the refining industry's pulse: when the gap between raw and white prices exceeds refining costs, port refineries thrive; when it narrows, they idle [C5].

Chapter 29 - Traders

Between the mill gate and the refinery stand the trading houses, the industry's invisible middle. Their business is origination, freight, finance and risk: buying raw sugar where it is surplus and selling where it is needed. The trade is old. ED&F Man traces to James Man, a London barrel-maker and sugar broker of 1783 who won the Royal Navy's rum contract in 1784 and held it until the daily tot ended in 1970 [C50]. The firm moved to Mincing Lane in 1810 and took its modern name from Man's grandsons in 1869 [C50]. C. Czarnikow began with Julius Caesar Czarnikow, a German-born broker who opened his City firm in 1861, built it into the leading house for colonial produce, and was a founder member of the London Produce Clearing House in 1888; the firm is owned today 42.5 percent each by Associated British Foods and Macquarie Group, with the remaining 15 percent held by an employee benefit trust [E43, C125, C124].

What such a house actually does becomes concrete by assembling one composite cargo from documented pieces: the grower pricing from Queensland, the contract standard from the ICE rulebook, the finance and hedging from Czarnikow's published accounts. At the field end, a Queensland grower is paid by a formula driven by the cane's measured CCS sugar content and the season's Net Sugar Price, and QSL's pricing fact sheet explains that the ICE No. 11 futures price represents approximately 99 percent of that Net Sugar Price (a five-year average for QSL-managed sugar), so for QSL's growers the world futures market, not a local buyer, does nearly all the price-setting (Chapter 12) [C52]. The cargo itself trades against the same contract's standard: 112,000-pound lots of 96-degree-polarisation raws, delivered FOB receiver's vessel at the port of origin, which is why physical sugar is quoted as a differential to a futures price (Chapter 30) [C3]. The financing differs by origin. In Queensland much of it is carried inside the industry structure: the miller-owned marketer, Queensland Sugar Limited, sells the season's sugar, makes advance payments to growers ahead of those sales, and charges the finance back to the pool as a marketing cost [C52]. Where no such body exists, a trading house's balance sheet does the work instead: in Brazil, Czarnikow's 2024 accounts record its local desk drawing US$270 million in credit lines from 18 local banks, financing one million tonnes of local origination within a record 3.8 million tonnes of agriproducts - not sugar alone - originated that year [C80]. The price risk runs the other way: the same accounts describe a principally fee-based model in which price movements are mitigated by hedging in the corresponding derivatives markets or by back-to-back purchase-and-sale agreements, the mechanism by which a trader earns a service margin without betting the house on the market's direction [C80]. The freight leg is its own market, fought over in

Chapter 33's terminals [C23]. And the spread between the raw contract and the white contract, the white premium of Chapter 30, is the gross refining spread the market pays, a spread traded in its own right [C5]. Each of these services exists because it is cheaper for a specialist to aggregate it than for each principal to carry it alone: a grower cannot wait months for payment, and financing, freight and hedging are businesses of scale [C52, C80]. That book lays off price risk, not counterparty risk: every physical leg still carries a counterparty who might fail, and the trader manages that exposure through credit assessment, limits and margining rather than through the hedge itself.

The modern structure is a small club whose members are mostly private and report their own scale. Wilmar International, in its 2024 annual report, says its sugar arm trades about 16 million tonnes a year, nearly 27 percent of global traded volume, a book built partly by acquiring Bunge's sugar trading business when Bunge exited [C1]. Alvean, created in 2014 by merging Cargill's and Copersucar's sugar trading, was described by Reuters at the 2021 split as the world's largest sugar trader, moving about 12 million tonnes a year, roughly 20 percent of global trade, when Cargill sold its half to Copersucar in 2021, leaving the sugar trading business in Reuters' wording [C12]. Sucden of Paris, founded in 1952 as Sucres et Denrees by Maurice Varsano and Jacques Roboh out of post-war Morocco trading, remains independent and family-owned, and describes a business of some 5,500 people across more than 25 locations moving over 10 million tonnes of soft commodities a year, sugar the historic core [C53, C48]. The pattern across two decades is of generalist houses selling physical positions while producer-linked specialists consolidated the flow: Cargill sold out of Alvean; Bunge's book went to Wilmar; and Louis Dreyfus sold Biosev, its Brazilian milling arm of nine mills and some 32 million tonnes of cane-crushing capacity, to Raizen in 2021 for R$3.6 billion plus equity, an exit from owning Brazilian mills, distinct from the trading book itself [C1, C12, C54, C55]. The state-linked exception is COFCO, China's main import channel, which describes handling about 6 million tonnes of raw sugar a year, roughly half of Chinese import volume [C56, C57].

Concentration here concentrates market intelligence itself. Most houses are private and disclose little, but Czarnikow's published accounts give one clean look inside: 2024 revenue of US$5.1 billion against a net revenue of about US$97 million, 423 people in 13 offices, running on group credit facilities of US$1.58 billion, the margins of a physical trader laid bare [C80]. The same accounts describe the model's modern extensions: divisions spanning market intelligence, agriproducts and food ingredients and packaging, and a sustainability programme, VIVE, run through the supply base, the modern trader as service company as much as speculator [C80].

PART X - THE COMMODITY

Chapter 30 - Markets and contracts

Sugar is priced in two cities and one unit that survives from another era: the American cent per pound. Nearly every tonne of raw sugar that crosses an ocean is priced off a single futures contract, the ICE Sugar No. 11 in New York, and nearly every tonne of white sugar off its London counterpart, the ICE White Sugar future. Understanding those two contracts - what exactly they promise, to whom, and where - is most of understanding how the modern industry prices its product.

The New York contract is a precise description of ordinary commerce. One lot is 112,000 pounds of raw cane sugar, about 51 metric tonnes, quoted in cents and hundredths of a cent per pound, with a minimum price movement of one-hundredth of a cent, worth $11.20 per contract [C3]. Delivery months run on a March, May, July and October cycle, and there is no daily price limit, a reminder that sugar is allowed to move [C3]. The grade is not a confectioner's product but the raw material of the trade: raw centrifugal cane sugar based on 96 degrees average polarisation, the brown, sticky crystal a port refinery buys [C3]. Settlement is physical, and the delivery terms are the trade's terms: free on board the receiver's vessel at a port in the country of origin, from a list of twenty-nine named deliverable origins on the exchange's current contract specification, running from Argentina and Australia to Thailand and Zimbabwe [C3]. A seller who is short the contract and stays to delivery must do exactly what an exporter does - load raw sugar in bulk onto a ship at an origin port. The contract works as a benchmark because it is simply the physical trade, standardised.

London's White Sugar future does the same job for the refined product. The contract is fifty tonnes, quoted in dollars and cents per metric tonne, with a ten-cent tick worth five dollars [C4]. Its grade admits white beet, cane crystal or refined sugar of the current crop, free-running, of fair average quality for its declared origin, with a minimum polarisation of 99.8 degrees, moisture no higher than 0.06 percent, and colour no higher than 45 units on the ICUMSA scale [C4]. Delivery is FOB and stowed in the vessel's hold at a port in any of forty-nine deliverable countries of production on the current specification, a far longer list than the raw contract's, because whites can come from any refining centre, beet factory or cane mill [C4]. Its calendar is denser too: five cycles a year - March, May, August, October and December - so that fourteen delivery months are listed at any time, letting a refiner or buyer deal nearly two and a half years forward [C4, C5]. The exchange describes its users plainly: the international sugar trade, millers, refiners and end-user manufacturers, alongside managed funds and institutional and short-term investors [C4].

A third contract completes the map by marking an exception. ICE's Sugar No. 16 prices the United States' domestic raw sugar market, which the American import regime keeps walled off from the world market - the policy machinery is Chapter 32's subject, but its footprint is visible here as a separate price. An ICE trading brochure from the early 2010s records that No. 16 often traded 35 to 50 percent above No. 11, and that the gap had at times approached three to one [C6]. The world price, in other words, is not the price much of the world pays; the futures board itself shows the seams.

Because the contracts are benchmarks, the industry's daily reference numbers are built from them mechanically. The International Sugar Organization's Daily Price, the number newspapers and contracts mean when they quote "the world price of sugar," is a simple average of the closing quotes of the first three futures positions of the New York No. 11; its White Sugar Price Index is the same average over the first two positions of the London white contract, and on days the New York market is closed an average is calculated under Statistical Rule S-14 of the 1992 International Sugar Agreement [C7]. Nobody trades the ISO price itself. It is a mirror of the board, and its long swings are the subject of the next chapter.

Physical sugar rarely trades at the flat benchmark price; it trades at a differential to it. A cargo of Brazilian raws or Australian raws is quoted as so many points over or under a named No. 11 position, with the invoice price settled against the futures settlement price when the ship loads, plus adjustments for the sugar's actual polarisation and any other negotiated components [C52]. This basis trading is why the futures market and the physical market cannot drift apart: the futures price is inside every physical invoice, and the possibility of delivery into the contract keeps the paper price honest against real sugar. The grower at the far end of the chain feels the same board: Queensland's industry fact sheet calculates that the ICE No. 11 price represents approximately 99 percent of the Net Sugar Price from which its growers are paid, the remainder being small marketing premiums and costs [C52]. A cane farmer in Burdekin who has never heard the words "futures contract" is, in effect, short New York sugar from the day the crop is planted.

Between the two world contracts sits the industry's most watched derived number: the white premium, the difference between the white and raw prices. It is the gross refining spread made visible, not the refiner's profit - processing, energy, freight, quality and financing costs all come out of it before any margin is earned [C5]. Even so it does economic work, because it tells the world's port refineries how hard to run. When the premium exceeds a refiner's full costs, refining pays and raws flow toward the refineries; when it narrows below those costs, the same plants lose money on every tonne and raws back up at origin.

The premium averaged an unusually high 126 dollars per tonne over the 2021-24 base period, on tight supplies [S22]. Nor is it only an observation: the spread is tradable in its own right, bought and sold forward across the white contract's fourteen listed months, and the classic position - long New York raws, short London whites - is the refining margin expressed as a trade [C5, C6].

That spread explains a structural shift in the trade itself. Over recent decades many large importing countries, particularly in the Middle East, stopped buying refined sugar and built their own port refineries to import raws instead, a shift an ICE brochure credits with pulling raw sugar prices up relative to whites [C6]. Chapter 28 examines the refiners; here the point is the contract geometry. Destination refining is the white premium turned into concrete: a refinery at an import port is a standing bet that the spread between the two futures boards will cover the cost of melting raws. The economics persist, the brochure notes, because raws are always cheaper than whites, raws are cheaper to transport, local markets trust locally refined supply, and governments favour the local jobs a refinery brings [C6].

The paper market grew slowly into this central role. Futures have traded in New York since 1914, on an exchange lineage running from the Coffee Exchange of 1882 through the Coffee, Sugar and Cocoa Exchange and the New York Board of Trade to ICE's takeover in 2007; options on sugar futures arrived only in 1982 [C6, E7]. Volumes are vast: ICE reported record total futures and options average daily volume in 2024, up 24 percent on the year across its whole exchange, though its release does not break out sugar alone [C63]. And because every contract is quoted in United States dollars, the market hands each grower a second, silent position: a Brazilian or Australian producer whose costs are in reais or dollars of another kind is long the sugar price and short the dollar at once, a currency exposure the exchange itself markets hedges against [C6].

Futures markets exist because sugar's physical world is slow and its price is fast. A mill commits a season's production months before it is crushed; a refiner buys raws months before selling whites; a soft-drink maker buys sweetness years of budget cycles at a time. The contracts let each of them lock a price or a margin today for sugar that does not yet exist, and they let speculators - the funds the exchange names among its own users - carry the risk in between [C4]. What that risk looks like when it detonates, across a century of booms, crashes and cartels, is the next chapter.

Chapter 31 - The price story

Sugar's price history is a history of violence: sudden, enormous swings that made and ruined whole economies. The documented landmarks mark the arc. In 1919-20 the "Dance of the Millions" sent the world price to giddy heights and then nearly to zero, breaking planters across Cuba and Java in a single season [S36, E10]. In 1974 world free-market sugar ran from 15 cents a pound in January to 34 cents by September, the contemporary American intelligence assessment of that year's market records [C93]. In February 2011 world raws hit a thirty-year high of 36.08 cents a pound on the New York exchange as a category-five cyclone bore down on Australia's cane belt and a market already tightened by uncertainty over Indian exports and Brazil's ethanol diversion took fright [C9b]. In 2023 the spike returned: drought fears in India and Thailand, an expected Indian export ban and an El Nino year drove London whites to a twelve-year high near 740 dollars a tonne and pulled raws up with them, the white premium blowing out as refiners bid for raws [C61, C62]. Between the spikes lie the long gluts, years when the world grows more sugar than it can sell and the price sinks below the cost of growing it.

The cycle's engine is the crop itself. Sugar takes a year or more to grow, so supply answers this year's price next year; drought in Brazil or India can cut output by millions of tonnes in a season; and Brazil's sugar-ethanol swing adds a fuel-market gear to the food market [S22]. Government policies damp or amplify: the US programme holds American prices structurally above world levels, two to three times the world price across a quarter-century by a Commerce Department study, while the EU's 2017 quota abolition let European prices fall to world levels and squeezed its own industry, until the 2022 energy crisis blew the gap between EU and world prices to 283 euros a tonne by February 2023, easing to 156 by that September [C28, C2, C90].

How political is sugar as a commodity? The historical record answers: completely. Import duties built fortunes and provoked a revolution, and international cartels tried for a century to manage the price, from the 1931 Chadbourne Plan through the International Sugar Agreements, none able to hold a price against a big surplus or a drought [E21, E25]. Chapter 32 sets out that policy machinery; here the point is what it did to prices. The twenty-first century's version of the question, whether concentrated exporters and traders can shape the market, is live: Brazil alone is expected to supply half of world trade in the current season [S22]. Chapter 32 follows the flows that carry that power.

The current cycle, 2023 to 2026

The most recent turn of the wheel is documented closely enough to narrate end to end, and it shows the cycle's whole machinery in one pass. The upswing crested in late 2023, the twelve-year high narrated above [C61, C62]. High prices did what high prices do. Brazilian centre-south mills, free to swing between sugar and ethanol, were projected to favour sugar through the period, and the USDA forecast India recovering to 33.6 million tonnes in 2026/27 with Thailand at 9.5 million [S22, C92]. By the time the USDA's May 2026 assessment was published, it was revising 2025/26 world production to 186.1 million tonnes and forecasting 184.9 million for 2026/27, with world exports at 62.3 million tonnes [C92].

The price told the rest. The ISO Daily Price, 20.32 cents a pound as a daily average across 2024, stood at 18.98 cents on 29 October 2026 [C7, C8]. The crash side of the cycle lands on producers asymmetrically, and the current casualties are in the accounting records. Nordzucker, Europe's second-largest beet producer, reported its 2025/26 results: 2.8 million tonnes of beet sugar and 0.6 of cane on 2.3 billion euros of revenue, and a 226-million-euro operating loss [C72]. That is what the glut phase of the sugar cycle does to a high-cost producer: the crop was grown, the factories ran, the sugar sold, and the margin vanished.

The cycle's political weather changed with it. During the 2023 spike the gap between EU and world prices blew out to 283 euros a tonne in February of that year, a measure of how tight Europe's own supply had become; by September it had eased to 156 [C90]. The American programme kept its own market sealed off at two to three times the world price, as it has for a quarter-century by the Commerce Department's accounting, so the crash phase that bankrupts a German beet processor barely registers in an American supermarket [C28]. One world price, several national realities: the cycle is global, but its wreckage is distributed by policy.

Chapter 32 - Trade flows

Most sugar is eaten near where it is made; the roughly 30 percent that crosses borders, over 60 million tonnes a year, carries the industry's geopolitics [C1]. The dominant flow is raw cane sugar from tropical exporters to refineries in importing countries, with the world split between about 60 percent raw and 40 percent white trade, a balance held stable by the logistics of bulk versus bag [S22].

The export side is a narrow club. Brazil is expected to secure about 50 percent of global sugar trade in the current season, overwhelmingly as raws; Thailand and India follow at distance, with Australia, Guatemala and the EU filling out the map [S22]. On the import side, China and Indonesia were the top two buyers over the 2021-24 base period, followed by the United States; the Outlook projects the growth in Asian and African imports and declining imports by the EU, US and Russia as their own production rises [S22]. The WITS/Comtrade record for 2024 puts actual values and volumes by country to these flows [S35].

The map still moves. In January 2026 the EU and Mercosur signed their long-negotiated agreement, which provides duty-free access for 180,000 tonnes of raw cane sugar for refining once it enters into force; ratification was still pending when the April 2026 attache report went to press; as of that report the concession was signed but not yet operative [C127]. Under Brazilian federal legislation the country's share of the new quota is reserved for its North-Northeast producers [C127]. Brazil held the second-largest share of the US tariff-rate quota as of that report, about 14 percent, and has consistently filled its allocation [C127]. And the biggest flow of all is expected to narrow a little: the April 2026 attache forecast puts Brazilian exports at 33.6 million tonnes in 2026/27, about 29.5 million raw and 4.1 refined, easing as higher gasoline prices pull the cane mix toward ethanol, a shift that would deepen if the government's study of raising the gasoline blend from 30 to 32 percent, announced that month, becomes policy [C127].

Two structural quirks deserve note. Some large producers are also large importers: countries with port refineries, like the United States and historically the EU, import raws while exporting or consuming whites, a pattern that reveals where refining margin sits [C22, C5]. And policy walls bend every flow: the US tariff-rate quota system rations access to its premium domestic market country by country; the EU's Everything But Arms initiative gives least-developed exporters duty-free entry; India's export permissions open and close by season [E3, E48b, C61]. Trade in sugar is never just trade; it is rationing, diplomacy and development policy wearing a customs code. The costs are measurable: a 2005 US Commerce Department study estimated that more than 10,000 jobs in

sugar-containing-product manufacturing disappeared between 1997 and 2002, nearly three confectionery jobs lost for every sugar-growing job the high price saved [C28].

Those walls have a four-century pedigree, and the chronology is worth setting down in one place because it explains today's map. Sugar was an enumerated commodity under England's Navigation Acts from 1660: colonial sugar could ship only to England or its colonies, a rule systematically enforced only from 1696 and resented most where it bit hardest [E23]. The Molasses Act of 1733 set a prohibitive duty at the West India planters' insistence and was nullified by smuggling; the Sugar Act of 1764 halved the duty but enforced it for revenue, and became one of the grievances on the road to the American Revolution [E21]. The nineteenth century ran on duties and bounties, the United States taxing sugar for revenue from 1789, repealing and restoring, while Britain's 1846 equalisation of colonial and foreign duties broke the West India interest's protection [E3, E17]. The twentieth century turned duties into quotas: the Jones-Costigan Act of 1934 built the American quota system that, amended through successive farm bills, still rations imports to a guaranteed domestic market share today [E3]. Britain's fiscal stake ran long and deep: duties around 34 percent ad valorem on muscovado helped carry sugar from luxury to what contemporaries called a decency of life [E47]. Europe's version was the 1968 Common Market Organisation, quotas plus a support price above world level, reformed in 2006 at a cost of 5.4 billion euros and abolished on 30 September 2017 [E2]. The preference ladder had its own chronology: the Commonwealth Sugar Agreement ran from 1950 to 1974, then passed into the 1975 Lome Convention's Sugar Protocol, which guaranteed African, Caribbean and Pacific exporters some 1.28 million tonnes a year at negotiated prices, Mauritius alone holding 487,200 tonnes; the Everything But Arms initiative of 2001 opened the EU to least-developed exporters, with sugar, rice and bananas on delayed schedules, sugar reaching full duty-free, quota-free access in 2009, and erosion of those preferences has been a slow-motion crisis for the smallest cane economies ever since [E33, E48, E48b]. And the world tried, repeatedly, to manage the whole market by treaty: the 1937 London agreement created the International Sugar Council, and the 1968 UNCTAD agreement created the International Sugar Organization that still sits in London [E25]. Every one of these regimes moved trade flows as surely as weather did.

Chapter 33 - Storage and logistics

Sugar's physical journey after the factory is a bulk-materials problem with quirks all its own, and the quirks start with time. Cane is crushed in a campaign of a few months and beets in a few weeks, but consumers eat sugar every day of the year, so nearly every tonne the industry makes must spend part of its life sitting still, waiting. Raw sugar waits well - it is a robust, flowing bulk solid - but only on the industry's terms: it is hygroscopic, and fresh sugar arrives at storage with residual moisture that will set a whole silo into a solid cake if the air around it is not managed [C78]. The engineering answer is the conditioned silo: stored air whose quantity, humidity and temperature are set continuously against the sugar's residual moisture, crystal size and feed rate, because a caked silo is a dead asset and clearing one is dangerous manual work [C78].

Before any of that comes the field chain, the shortest and most unforgiving leg. Cut cane cannot wait - its sugar starts to deteriorate with the stalk - so every cane district is built around a transport system that runs like a conveyor. The classic solution was the cane railway: dedicated narrow-gauge networks in Queensland, Fiji, Java and Cuba, built for one crop and shaping settlement around the mills, several still working today, others surviving as heritage lines (Chapter 35) [E13, E11]. Queensland's network is the scale benchmark: an industry historian's account puts it at more than 3,500 kilometres of 610-millimetre gauge hauling over 24 million tonnes of cane a year, on a clock that moves cane from field to crushing within about 24 hours of the cut, with transport absorbing roughly 30 to 40 percent of milling cost [E34]. Where railways gave way, road trains and infield transporters took the same clock over.

The mid-twentieth century brought the transformation that made the modern trade possible: the shift from bags to bulk. For centuries sugar moved in sacks, handled tonne by tonne; the change to loose bulk handling turned ports into processing plants in their own right. The Swedish industry's record traces the concrete silo designs to Great Western Sugar in the United States in 1930, credits engineer Nils Weibull with the first steel silo for bulk handling in 1933, and marks 1957 - "after the international breakthrough of bulk handling of cane raw sugar" - as the year a 10,000-tonne raw-sugar silo went up at Malmo harbour to receive and load ships directly [C77]. The white-sugar versions followed immediately: the first two 20,000-tonne granulated-sugar silos were built in 1956, and by 1961 a 30,000-tonne conversion stood as the largest [C77]. Bulk terminals did for sugar what they did for grain and ore: they collapsed the cost of the port leg and made a world market in a cheap commodity physically practical.

The most complete version of that system operates in Queensland, and its FY25 record shows what the machinery looks like at full stretch. Six bulk sugar terminals, owned collectively by the industry through the publicly listed Sugar Terminals Limited, receive raw sugar from the mills, store it in vast sheds, and load it directly into ocean vessels [C23]. For decades the terminals were operated by Queensland Sugar Limited, the industry's not-for-profit marketer, as a pass-through service; in fiscal 2025 its teams loaded 96 sugar ships and delivered 95 of them in-full, on-time and in-specification - a 99.0 percent DIFOTIS score - alongside 52 other vessels, including 49 molasses cargoes [C23]. The terminals are not a free good: growers' pool accounts in FY25 carried storage and handling costs of 34.14 Australian dollars per tonne, including payments to Sugar Terminals Limited, and the benchmark against which QSL's pool pricing is measured is explicitly adjusted for infrastructure, storage and production-risk constraints [C23]. Assets this critical are contested. QSL's multi-decade operating agreement ended on 30 June 2026 after a long dispute in which QSL itself argued that entrusting the terminals to a for-profit owner-operator brought disruption, cost and risk, and pointed out that grower-economic-interest sugar made up two-thirds of terminal throughput while mill owners held the voting control of STL [C23]. The owner completed its insourcing on schedule on 1 July 2026, reporting no interruption to receivals or shipping, with the operations staff moving across - the company's own account of a change whose merits the industry still debates [C23b].

The ocean leg is bulk freight, bought in the same market that moves grain and coal, and the terms are written into the commodity contract itself: raw sugar loads FOB the receiver's vessel at a port in the country of origin, exactly as the No. 11 contract specifies [C3]. Freight is therefore not an afterthought but a second price every exporter wears, and it has its own weather. Queensland's marketer reported FY25 rates knocked sideways in both directions: delayed grain loadings in Brazil and Australia briefly softened the market, then a strong South American grain crop drew vessels away from the Pacific and supported rates; growth in Chinese steel exports and shifting coal flows favoured smaller vessel classes; and through it all bulk carriers kept diverting around the Cape of Good Hope, a geopolitical surcharge landing directly in the cane grower's freight bill [C23]. Against that market QSL contracted and delivered 36 raw-sugar cargoes in the year with a 100 percent on-time, in-full record [C23]. A Queensland grower's net price is, in the end, a futures price minus this logistics: the industry's own accounting puts terminal storage, handling and the finance charges of the physical chain at roughly seven percent of the net sugar price [C52].

At the destination port the flow splits, and the first branch barely touches land. The port refinery takes raws straight from the berth into the melt house, a

logistics arrangement so compact that the refinery is best understood as a ship-unloader with a factory attached. Dubai's Al Khaleej refinery at Jebel Ali is the standing example: it imports raw sugar from Brazil, India, Australia and Thailand, credits the port's logistics for its model, and has grown since July 1995 from 6,000 to 7,000 tonnes a day - with a record 1.87 million tonnes in 2017, about three percent of global refined output by its own account, exported onward to more than 50 countries [C22]. The lineage is old: London's great refineries, Henry Tate's Thames Refinery of 1878 and Abram Lyle's Plaistow Wharf of 1882, were built on the same principle of sucking raw sugar off ships at the dockside [C16].

The second branch is the white trade, and it is a different logistics entirely. Refined sugar cannot be poured into a ship's hold like raws; it moves bagged or containerised, a parcel trade of warehouses and box ships in which Czarnikow, the old London house, claims the volume lead in containerised whites [E43]. A growing slice never crystallises into a bag at all: liquid sugar moves to industrial users as a ready-to-use input, pumped into automated dosing systems without the buyer ever handling a crystal - no dissolving step, no empty bags, no sugar dust - a delivery format the European producers have run since the 1970s [C31]. The closer sugar gets to the food factory, the more its logistics become a utility service rather than a trade.

Brazil, the largest flow in world sugar, solves the same problem in the opposite way, and the contrast is the chapter's lesson. More than 90 percent of Brazilian sugar grows in the centre-south, an average of more than 500 kilometres from the sea, and roughly two-thirds of the country's exports funnel through a single port, Santos [C128]. A 2025 logistics study drawing on regulator and port data records how the 2024 crop reached the quay: 47 percent by truck, and the rest by rail split between three private concession operators - VLI with 29 percent, Rumo with 13 and MRS with 11 - feeding through eleven road-rail transfer terminals in Sao Paulo and Minas Gerais that move over 12 million tonnes a year, down to four discharge terminals at the port with 18 million tonnes of combined annual capacity [C128]. Where Queensland collectivised its terminals into an industry utility and fought for decades over who should run them, Brazil privatised its railways and lets the concessions carry the crop. Both answers work. Both also show the same truth from opposite ends: in a commodity whose margins are counted in single digits, the storage shed, the railway and the berth are not overheads on the business - in large part they are the business, and whoever controls them holds a quiet power over everyone who grows the cane.

PART XI - SUGAR AND SOCIETY

Chapter 34 - Labour

No commodity in human history has been worked by more unfree hands than sugar. The statement is made carefully, and the numbers behind it are documented. Of the roughly 12.5 million Africans loaded onto slave ships between 1501 and 1866, about 10.7 million survived the crossing, and the scholars who maintain the standard voyage database conclude that sugar plantations absorbed well over two-thirds of the captives carried by the major slaving powers; their summary mapping essay puts it more starkly still: about eighty percent of all captives taken from Africa went to sugar-growing areas [EC-1, EC-2, EC-3]. Between 12 and 13 percent of those embarked did not survive the Middle Passage itself - an average, the same scholars note, driven up by catastrophes on a minority of voyages, with more than a quarter of the captives classed as children [EC-2]. This was not an incidental labour force attached to an ordinary crop. It was the labour force the crop demanded, assembled by violence because no other supply answered.

Why sugar demanded coercion

Sugar's labour problem is written into the plant and the process. Cane yields a harvest that must be crushed within days of cutting or the sucrose spoils (Chapter 11), so the crop demands a concentrated burst of heavy field labour precisely synchronized with continuous factory labour - boilers and batteries that run day and night through the campaign. Tobacco could be tended by a family; cotton picking could be paced. Sugar could not. Historians have long noted that sugar required more labour, more capital and more managerial expertise than the other plantation staples, and that the harvest-and-crush calendar could not wait on anyone's willingness [S2, S3]. The mill's appetite set the rhythm, and the rhythm was set by chemistry, not by negotiation. Every labour regime sugar has ever run - enslaved African gangs, indentured Indians, Queensland Islanders, modern hand-cutters and mechanical harvest crews - is an answer to that same constraint.

The workforce was rebuilt as each source failed or was closed. Indigenous labour was tried first in the Americas and collapsed with indigenous populations under disease and exploitation. European indentured servants followed, but free migrants and servants never crossed the Atlantic in the numbers the plantations needed - as late as 1820, nearly four Africans had crossed for every European - and Europeans, as the slave-trade historians put it, proved unable to enslave other Europeans at scale [EC-2]. African chattel slavery filled the gap, and in the British Caribbean it was codified into racial caste law in the mid-seventeenth century, just as the sugar revolution took hold [E1, E15]. After

emancipation the industry reached east and built the indenture system from India, China and the Pacific, a regime historians still argue how to name [E17].

The plantation regime

Work on a sugar estate was organized to extract the campaign the mill required. Field labour ran in gangs - in the British Caribbean, by the later decades of slavery, the great gangs were majority-female, a documented demographic reality that cuts against the period's own imagery of field work as men's work [E1]. The lethality of the regime exceeded that of other plantation crops: exhaustive field work in tropical heat, night shifts at the mills in crop time, disease environments the workforce had no immunity to, and punishment systems built to keep the whole machine on schedule [S3]. On the demographic evidence, the British and French Caribbean estates consumed their workforces - deaths exceeded births on the sugar islands for most of the slavery era - which is one reason the Atlantic trade kept running: the plantations did not reproduce their own labour, they replaced it [E15]. Historian Ulbe Bosma estimates that as late as the 1860s, half the sugar consumed by the industrial workers of Europe and North America was still grown by enslaved people, a reminder that emancipation in the British colonies in the 1830s did not end slave-grown sugar; it merely changed which flag it sailed under - above all to Cuba and Brazil [S3, E10].

Emancipation, engineered for the industry

When Britain abolished slavery in 1833, the settlement was designed around the industry's survival, not the freed people's compensation. The enslaved were freed only through an "apprenticeship" of further unpaid labour that ran to 1838, and the twenty million pounds voted by Parliament went not to the emancipated but to their owners [E8]. The Bank of England's own study of the payout's mechanics describes the machine: compensation for more than 800,000 emancipated people across the empire, paid partly in 3.5 percent government annuities rather than cash, collected on behalf of absentee owners through a small ring of London banks and merchant houses, and converted to cash almost at once [E8, E24]. The Slave Compensation Commission's records - more than 40,000 owners named - remain a near-complete census of who profited, and the UCL Legacies of British Slavery project has spent fifteen years tracing where that money went next: into banking, insurance, railways, and industrial ventures [E16].

What emancipation did not bring was free labour on free terms. Planters across the British West Indies moved to close off the freed people's alternatives, and the economic mechanism is now unusually well documented. Using data from fourteen British West Indian sugar islands between emancipation in 1838 and

1913, economists Christian Dippel, Avner Greif and Daniel Trefler show that planters lobbied colonial governments for coercive policies - the eviction and incarceration of squatting smallholders - precisely to degrade workers' outside options in the informal economy, and that where geography made escaping the plantation system easier, planter power declined, incarceration fell, and agricultural wages rose. Most of the wage increase can be statistically explained by the reduced coercion of smallholders [EC-4]. The finding matters beyond the Caribbean: it is the clearest formal demonstration that post-slavery sugar wages were not set by a labour market alone, but by the political suppression of the alternatives to estate work.

Indenture: the debate that will not close

Indenture replaced slavery on terms historians still argue how to name. Between the 1830s and the system's end in 1917, more than 1.6 million Indians were transported under contract to sugar colonies from Mauritius and Natal to Fiji and the Caribbean: five-year "girmit" terms at fixed wages, criminal penalties for breach of contract, mortality on some early voyages above 17 percent, and deception in recruitment common enough that Hugh Tinker's landmark history titles the whole system "a new system of slavery" [E17, EC-2]. Other historians frame indenture as coerced but contractual migration - closer to the earlier European servant trade than to chattel slavery - and the evidence supports elements of both readings: contracts were real and sometimes enforced, time-expired workers could and did return or re-indenture, and large free Indian communities grew from the system; and the contracts were also signed by people who often could not read them, recruited by men paid per head, enforced by criminal law, and worked on estates whose owners and managers were drawn from the same class that had run the slave gangs [E17]. This book presents the debate rather than settling it.

Queensland's version was harsher in recruitment and colder in disposal. Between 1863 and 1904 the colony took over 62,000 South Sea Islanders for its cane fields, many recruited by deception and some kidnapped outright - "blackbirding" in the period's own euphemism - and when the new Commonwealth passed the Pacific Island Labourers Act in 1901, it deported most of the Islander population their labour had built [E12]. Fiji's cane fields were built on Indian girmit from 1879 under a single company, CSR, and the indenture system's end there did not end the contest between labour and capital - it continued through strikes and the smallholder transition into the industry settlement Chapter 35 records [E28]. The Asian contract-labour trades that sugar created ended only in 1917, half a century after the last Atlantic slave voyage [EC-2].

Free labour, still hard

Modern sugar labour is legally free, and the work is still among the hardest in agriculture. More than half the world's cane is still cut by hand, in heat, by the tonne - a tertiary-source figure the industry does not dispute, and one that varies sharply by country [S2b]. Machines replaced the gang where terrain and wages allowed, at the pace Chapter 11 records [S-C13]. The modern era's starkest documented cost is the chronic kidney disease epidemic of Mesoamerica's Pacific coast, where young agricultural workers - sugarcane cutters prominent among them - have suffered kidney failure at rates without parallel; the Pan American Health Organization classified it as a major public health problem for the region in 2014. A systematic review and meta-analysis of twenty-five epidemiological studies finds the condition strongly associated with being male, with lowland residence, and with family history of kidney disease - and, importantly for honest accounting, finds no significant association yet established for pesticide exposure, NSAID use, or even heat stress itself, the most-discussed suspect. The disease is real and concentrated in cane-cutting communities; its cause remains officially "of undetermined etiology," and this book reports it that way [EC-5, S2b].

Where institutions reach, conditions improve, and the record shows both halves. Brazil is the test case: as harvest mechanization reached about 90 percent of national production, employment in manual cutting collapsed, taking with it the occupation where labour inspectors had concentrated their findings - analysis of 15,488 federal labour-violation notices issued against the sector between 2000 and 2019 shows irregularities clustered precisely in manual cane cutting, and falling as the machines spread [EC-6, S-C32]. Mechanization ended the worst jobs and also the jobs (Chapter 11 covers the machines; the labour consequence belongs here): a trade the industry and its unions still negotiate. Unions, certification schemes and lawsuits have changed terms where they operate; the CKDu epidemic shows what the absence of an enforceable water-shade-rest regime costs. Sugar's labour story does not end in the nineteenth century. It is the oldest continuously documented argument in the industry, and it is not over.

Chapter 35 - Economies built on sugar

Sugar did not merely grow in places; it organised them. The pattern repeated from Madeira to Mauritius: land surveyed into estates, labour imported by the shipful, ports and railways laid to the mills, towns and banks and trading houses raised on the crop's proceeds, and a politics bent around protecting it all. This chapter tours the economies sugar made, as case studies in one system - and then asks the harder question the system poses: how much of the modern economy did sugar build?

The plantation complex as an economic machine

The plantation was not a farm. It was an integrated production system that fused field and factory under one discipline, and it appeared wherever sugar went because the crop's chemistry required it (Chapter 34): cut cane spoils within days, so the mill must sit inside its own cane supply, and the mill's capital cost - boilers, trains of coppers, later vacuum pans and centrifuges - was far beyond any smallholder. Land, labour and factory had to be assembled together, at scale, before a single tonne could be sold. That is why sugar's geography is a geography of complexes rather than of crops: estate or central, cane railway or barge, port, merchant house, and a labour force assembled from elsewhere [E1, E13]. It is also why sugar regions so rarely diversified from within: the complex crowded out food production, monopolised the best land and the credit, and left its host economy with world-class infrastructure that served one commodity and no fallback when the price turned.

The Atlantic template: Barbados to Saint-Domingue

Barbados was the template. When James Drax bought a triple-roller mill and copper cauldrons from Dutch Brazil in 1640, the island switched from tobacco and cotton to cane, and within a generation became the richest European colony in the Caribbean, a position it held for roughly a century [E1]. By 1660 British sugar imports were worth more than all other colonial products combined [E15]. The template's elements - Dutch milling technology and credit, English capital and mercantile protection, African enslaved labour, and a metropolitan market - would be copied for two centuries.

Saint-Domingue outdid every rival. By the mid-eighteenth century it held the largest enslaved population in the West Indies, imported some 30,000 Africans a year, and produced more sugar than all the British West Indies together, on French irrigation engineering of reservoirs and aqueducts [E15, E1]. Its revolution destroyed the system in a decade. What followed is instructive for every sugar economy since: the plantations were not merely damaged, they

were broken into smallholdings, and one recent line of scholarship reads Haiti's missing sugar industry as a transaction-cost story - cane could not be re-established at estate scale because the land, labour and credit could not be reassembled under the post-revolution settlement [E1]. The plantation complex, once shattered, did not spontaneously re-form. Sugar economies are easier to destroy than to rebuild.

The nineteenth-century giants: Cuba and Java

Cuba inherited the crown and held it for nearly two centuries. Output climbed from about 55,000 tonnes in 1820 to roughly a million in 1895 and five million by 1925 [E10]. The island industrialised early, with railways laid field-to-port to serve the mills, and the industry's finance ran through American capital and American tariffs, a dependence that collapsed it twice: in the "dance of the millions" of 1920, when the post-war price spike reversed within months, breaking growers, mills and the banks that had lent to them, and again after 1991, when the Soviet Union's subsidy purchases ended [E10, E11]. The end-state is documented in Chapter 32's terms but belongs here as economic history: from around eight million tonnes in the late 1980s, the 2024-25 harvest fell below 150,000 tonnes against a state plan of 265,000 - press estimates ran near 165,000 - a level one analyst said requires going back to the nineteenth century to match [E42, E10]. Cuba is the extreme case of monoculture's bargain: the same crop built the island's railways, its banks, its cities and its politics, and the crop's collapse has unmanned them all.

Java was Asia's version. The island was the world's second cane-sugar exporter from about 1870 to 1930, first under the coercive state Cultivation System - at its peak supplying more than a third of the Dutch state's revenue - then under private estates served by colonial banks and by the Proefstation Oost-Java breeding station, whose science pushed Java to the world's highest yields by 1938, ten times those of a century earlier [E13, E49]. The industry collapsed in the Depression when its protected market vanished, and Indonesia today is one of the world's largest sugar importers [E49]. The long-run scholarly verdict on Java's sugar century is contested in a way this book deliberately preserves: Dell and Olken's village-level study finds the areas around the colonial factories today more industrialised, better educated and richer than comparable locations - the production-enabling structures the Dutch built outlasted the coercion - while the older reading of the Cultivation System as pure extraction has its own evidence [E49]. Both belong in the account, because both are what a sugar economy can leave behind.

Settler capital: Hawaii, Louisiana, Fiji

Hawaii built an oligarchy. The 1875 Reciprocity Treaty let Hawaiian sugar into the American market on favourable terms, and sugar revenue more than tripled in four years; five agencies - Ladd & Company, H. Hackfeld, C. Brewer, Castle & Cooke, Alexander & Baldwin, the Big Five - turned that leverage into political revolution in 1887, and the treaty's own dynamics, one economic history argues, contributed significantly to the 1893 overthrow of the Hawaiian Kingdom [E51, E52]. Louisiana built the antebellum South's most industrial agriculture: planters' banks and factor credit raised on the crop from the 1820s, steam-powered mills, and tariff lobbying from the same decade [E18]. Fiji kept the plantation model longest: CSR ran the industry on Indian indenture from 1879, and when the Denning arbitration of 1969 rewrote miller-grower terms, the company simply left, in 1973, handing the industry to the state and its smallholders [E28].

The metropolitan mirror

Every one of these producing economies had a mirror in the consuming one, and the mirror was also built of sugar. The commodity chain that ran from Caribbean field to British teacup generated value added worth about 1 percent of British GDP early in the eighteenth century and about 4 percent by its end - most of it captured not on the plantations but in the tertiary sector: shipping, insurance, brokerage, refining and distribution [E46]. Marine insurance on the slave-sugar routes made up perhaps a third to two-fifths of Lloyd's premium income in its peak decades [E45]. The broker C. Czarnikow built a global trading house on sugar from 1861 and helped found the London Produce Clearing House; the London trade organised itself in the Sugar Association of London from 1882; Havemeyer's trust consolidated American refining until the Supreme Court's E.C. Knight ruling and then beyond it [E43, E36, E30, E37, C20]. And the fiscal state fed on the flow: the customs duties of Chapter 32 helped carry sugar from luxury to what contemporaries called a decency of life, and the fiscal literature of the day tracked tea and sugar passing "from luxuries to decencies" as mass consumption made them dependable revenue [E47]. The emancipation settlement of 1833 recycled planter wealth one last time: the compensation machine of Chapter 34 flowed into the mid-Victorian capital market whose descendants the UCL project is still tracing [E24, E16].

How much of all this "caused" industrial modernity is a live scholarly fight, and this book maps it rather than settling it. Eric Williams argued in 1944 that the profits of the slave-sugar complex financed Britain's industrial revolution; the thesis has been attacked, defended and narrowed for eighty years. The current reassessment literature grants slavery's profits a large role in Atlantic commerce while disputing how much of industrial investment they can explain - the

difference between a sector that was large (Ronnback's 4 percent of GDP) and a cause that was decisive [E31, E32, E46].

The preference era and the escape from monoculture

In the twentieth century the plantation complex was succeeded by something quieter but no less organising: the preference. Guaranteed prices and quotas - the Commonwealth Sugar Agreement and then the Lome Convention's Sugar Protocol for the ACP exporters, the American import quota, the EU's intervention price - decided which economies could live by sugar and which could not, often independently of cost. Mauritius ran a whole island as one sugar economy inside the Commonwealth preference, then did the rarest thing: at independence in 1968 it chose rule of law over nationalisation of the plantations, kept the sugar rents and preferences coming, and used them to diversify into textiles, tourism and finance - the "Mauritian miracle" [E20, EC-7]. The preference regime that paid for that diversification was itself dismantled in stages: the EU's 2006 reform cut the intervention price by 36 percent, the Everything But Arms initiative from 2009 eroded ACP preferences further - gravity-model evidence confirms ACP exporters lost ground - and the 2017 end of EU quotas exposed the remaining preference economies to the world price [E33, E48]. The Philippines lived the same arc in a single generation: Nicholas Loney's credit-and-machinery opening of 1856 built the industry, the 1974 world-price spike from cents to sixty-seven cents a pound and the crash back to three broke it, and the country produced about 2.1 million tonnes in 2024/25, a middle-rank producer living with the bargain [E39].

What do the cases share? Monoculture's bargain: extraordinary first-generation wealth; infrastructure built for one crop; institutions captured by it; extreme exposure when the price or the preference turns. Sugar built railways, ports, refinery cities and trading houses; it also left islands that could not feed themselves and treasuries that could not survive a bad season. The economies that escaped monoculture escaped with sugar's own money, and usually through a door - a preference, a treaty, a timely diversification - that politics opened and politics could close. The ones that could not escape are still living the bargain.

Chapter 36 - Health and policy

The substance that built empires met its adversary in the twentieth century: medicine. The modern argument starts with definitions, and they are not interchangeable. The World Health Organization's category is "free sugars": sugars added to food by anyone, plus the sugars in honey, syrups, fruit juices and juice concentrates, but not the sugars inside intact fruit or milk [S-F10]. The American label category, "added sugars," is different again [S-F4], and the guideline literature mostly concerns free sugars [S-F10]. The WHO's 2015 guideline, still the global reference, makes two strong recommendations, reduce free sugars across the lifecourse and keep them under 10 percent of energy, and one conditional one, under 5 percent; and it grades its own evidence honestly: low to moderate quality for body weight, very low to moderate for dental caries [S-F10]. Actual consumption sits far above the guideline: caloric sweeteners run to more than 20 percent of dietary carbohydrates in the United States [S22].

What the best evidence shows is more specific than the headlines. The WHO-commissioned review of body weight found that eating less sugar ad libitum cuts about 0.8 kilograms and eating more adds about 0.75, but that swapping sugar for other carbohydrates calorie-for-calorie changes nothing, the authors' own framing is that the weight effect works through energy intake, not a unique toxicity of sugar itself [S-F11]. In children the trials are weaker: advice to cut sugar produced no measurable BMI effect across five randomised trials, with compliance poor and results heterogeneous, while cohort studies comparing the highest against the lowest sweetened-drink intake give an odds ratio of 1.55 for overweight, graded low quality; the null trial result is a compliance story, not proof of no effect [S-F10, S-F11]. For teeth, the commissioned review, which found no randomised trials at all, graded moderate-quality evidence that caries fall below 10 percent of energy from free sugars, with a log-linear dose relationship down to very low intakes: caries falls with sugar but never reaches zero [S-F12]. The gap between the guideline's two numbers is itself a lesson in evidence. The strong 10 percent line rests on moderate-quality cohort evidence, five cohort studies, all in children, all finding higher caries above a tenth of energy [S-F10]. The conditional 5 percent line rests on something much thinner: three ecological Japanese studies spanning the wartime years, when national sugar availability collapsed from 15 kilograms per person per year to a low of 0.2 and caries fell with it. Those are population availability figures, not individual intake, with no adjustment for confounders, which is why the evidence table grades them very low and the recommendation merely conditional [S-F10]. For diabetes, a meta-analysis of seventeen cohorts found each daily serving of sugar-sweetened beverages associated with 18 percent higher incidence before adjusting for adiposity and 13 percent after, an

association that does not prove causation but survives the adjustment [S-F15]. For cardiovascular death, an observational NHANES study found risk ratios above two at the highest added-sugar intakes, association, not proven causation [S-F20].

The body's handling of sugar explains why the argument concentrates on fructose, and where it stops. Sucrose is split at the intestinal wall into glucose and fructose before absorption [S-F6]. Glucose enters regulated metabolism; fructose is phosphorylated by an enzyme, ketohexokinase, that is not feedback-controlled, so a large fructose load floods the liver's machinery, depletes cellular energy and generates uric acid, a plausible link from sweetened drinks toward gout and fatty liver [S-F6]. Isotope-tracing work in mice found the small intestine, not the liver, clears about 90 percent of a modest fructose dose, with high doses spilling over to liver and gut microbes; the authors themselves caution their data are mouse data and do not establish human dose-response [S-F7]. The strongest human trial fed overweight adults drinks supplying 25 percent of energy as fructose or glucose for ten weeks: weight gain was similar, but only the fructose group gained visceral fat, raised blood lipids and lost insulin sensitivity, at a dose far above anything a sucrose-eater normally reaches, comparing two monosaccharides, not sugar against another sweetener [S-F25, S-F24]. And the genetic evidence cuts both ways: people born unable to metabolise fructose show high circulating fructose with no reported pathology, suggesting the metabolism, not the molecule, carries the risk [S-F6]. Even "sugar addiction" is an open dispute: Princeton's rodent studies show drug-like bingeing, withdrawal signs and dopamine release that never habituates, but only under intermittent access schedules, and critics answer that the paradigm measures access to tasty food, not a neurochemical effect of sugar itself, with little human evidence either way [S-F26, S-F23].

Governments have answered, so far, mainly at the drinks aisle. By the WHO's 2023 global report, at least 108 countries taxed sugar-sweetened beverages as of 2022 [S16]. The policy evidence is young but real: Britain's 2018 levy, tiered by sugar content, drove manufacturers to reformulate before it even took effect, and a year in, household purchases of the highest-tier drinks had fallen 37.8 percent by volume and their sugar by 42.6 percent, while total soft-drink volume actually rose slightly, the recipe changed more than the drinking [S-F17, C29, C30]. Taxes shift recipes more than they shift buying, which may be the more durable effect.

The industry's side of this history is darker than mere opposition. A 2016 review of sixty experimental studies on sugary drinks found that 25 of 26 studies reporting no harm had industry funding ties, against 1 of 34 finding harm, figures that survived a published correction of one miscoded study [S-F13]. The

industry's own archived documents, analysed in a 2016 historical study, show the Sugar Research Foundation sponsoring research from 1965 to cast doubt on sucrose's hazards while promoting fat as the culprit in heart disease, including a 1967 New England Journal of Medicine review whose industry funding and role were never disclosed [S16g]. The industry's modern position, that sugar in moderation fits a balanced diet, is not false; the argument is about what "moderation" can mean when one substance is engineered into nearly every packaged food [S3].

Policy beyond taxes is thinner. The OECD-FAO Outlook notes front-of-pack labelling laws, marketing restrictions to children, and reformulation programmes across Latin America and Europe [S22]. The WHO's 2023 guideline on non-sugar sweeteners advises, conditionally, against relying on them for weight control, short-term trials show small benefits, long-term evidence shows none, while leaving their safety approvals untouched [S-F16]. Meanwhile the projections of Chapter 39 show the tension plainly: health pressure bends per-capita consumption down in rich countries while population and income growth push total demand up elsewhere [S22]. Sugar's health reckoning is real, and it is losing, so far, to arithmetic.

Chapter 37 - Environment

Sugar's environmental account opens with an old offence, and Madeira shows its mechanism in miniature. The Atlantic island's sugar economy devoured its own foundations: no cash crop consumed forest as quickly as sugar, the boiling houses' fuel hunger removed half the island's accessible woodland within decades of settlement, and output collapsed from an average 1,900 tonnes a year in 1505-09 to barely 300 by the 1530s, even as the price of its best grades rose by half [E50]. The pattern then repeated across the Atlantic for four centuries: the plantation frontier cleared forests island by island, Hispaniola in the sixteenth century, Martinique in the seventeenth, Jamaica and Haiti in the eighteenth, Cuba and Puerto Rico in the nineteenth, and monoculture then mined the soil [E1]. Timber for fuel and construction grew so scarce in the seventeenth-century Caribbean that it drove inter-imperial conflict [E1]. The environmental historian Jason Moore's reading of the pattern is that the crisis was not misfortune visited on planters but the system's own logic: capital answered exhausted land less by mending it than by moving on, which made deforestation, exhaustion and frontier-moving the industry's founding environmental signature [E50].

The modern ledger has distinct entries. Water: a full cane crop is thirsty at the seasonal demand Chapter 9 numbers, met by rain where rain obliges and increasingly by irrigation where it does not, and the demand collides with scarcity in several producing regions [S-C1, S2b]. Nutrients and pesticides: Australia's 2022 Scientific Consensus Statement on reef water quality, the government-science consensus process, puts numbers on cane's share. Sugarcane covers some 400,000 hectares of the Great Barrier Reef catchment and contributes 42 percent of the total dissolved inorganic nitrogen load reaching it; and sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations, over 97 percent in some regions, mostly photosystem-II herbicides; and it contributes about a tenth of fine sediment, against grazing land's roughly three-fifths. The same statement finds several cane land-management practices proven cost-effective at improving water quality [S34]. Fire: pre-harvest burning clears fields fast and fills district air with smoke; mechanised green harvesting eliminates it and returns a mulch blanket that growers' own field guides credit with moisture retention, weed suppression and soil protection [S2b, S-C13]. The practice is retreating where machines advance and persisting where they have not; in Brazil, the largest producer, state law and a mill pledge have been closing the fire for two decades (Chapter 11) [S-C32]. Vinasse, ethanol's liquid stillage, shows the two faces most sharply. It is the main wastewater of ethanol production, and in Brazil its primary destination is the field itself: fertirrigation, pumping it back onto cane land for its potassium, a

practice Sao Paulo's environmental agency regulates by dose, with the K2O content of the applied vinasse determined weekly against the crop's own extraction of about 185 kilograms of K2O per hectare [C108, C109]. Managed that way, it is a fertiliser returned to its source. Mismanaged, it is a real pollutant: vinasse carries more than 4,000 milligrams per litre of dissolved solids and over 14 grams per litre of biodegradable organic matter, a combination that risks soil salinisation and, in water, the oxygen collapse of anaerobiosis [C108]. Whether the same liquid is asset or effluent depends on dose, soil, site and handling together.

There are also credits, and honesty requires them. Cane is an unusually efficient converter of sunlight to biomass (Chapter 2); bagasse power feeds grids at scale, cane residues supplying three-quarters of Brazil's biomass-based generation in 2024 [C98]; green-cane harvesting returns mulch to the soil [S2b]. The environmental comparison against other sweetener crops, and against the land that sugar's calories would otherwise require, is genuinely complex, and no simple verdict is honest.

The forward-looking question is climate itself. Cane's climatic envelope, frost-free and water-fed, is shifting [S22]. Beet's version of the exposure is the pest-regulation triangle, documented in France in 2020: after the 2018 ban on neonicotinoid seed treatments, a mild spring - the American agricultural service's own account of the trigger - brought an aphid infestation and with it virus yellows across the growing regions of the European Union's largest beet producer; with drought compounding the infestation, French experts estimated yields down 30 to 50 percent, and the government proposed exempting sugar beet from the ban for up to three years, seed treatment only [C106, C107]. A single season is weather, not climate; what the episode documents is how quickly the crop's pest exposure becomes a policy fight when protection is withdrawn. Britain's epidemic the same year, the largest aphid migration since national trapping began in 1965, is Chapter 10's case [S-C15]. Both industries now sell themselves as part of the climate answer through bioenergy while remaining exposed to the climate themselves [S22]. Chapter 41 takes up the bottleneck directly.

PART XII - RIVALS AND FUTURE

Chapter 38 - The substitutes

Sugar's monopoly on sweetness has been under attack for a century and a half, and the attackers fall into three families. The first is other caloric sweeteners, above all high-fructose corn syrup. HFCS is made by enzymatically converting glucose from maize starch partly into fructose; commercialised by the early 1980s, it priced itself against sugar and, in the United States, took the soft-drink industry within years, as Chapter 22 records [C94]. Globally it holds about 8 percent of the caloric sweetener market and is projected to stay there [S22]. Its rise was as much policy as chemistry: American maize abundance and American sugar import barriers made HFCS cheaper than sugar in the United States while the rest of the world mostly kept sucrose [C28].

The second family is the intense sweeteners, hundreds of times sweeter than sugar, contributing essentially no calories. Their history is a century of chemistry and regulation. Saccharin, the first, came out of coal-tar chemistry at Johns Hopkins in 1879, when Constantin Fahlberg, working in Ira Remsen's laboratory, noticed a sweet taste on his hand and traced it to the compound he had handled that day [C111]. Cyclamate followed from a similar laboratory accident in 1937, an Illinois graduate student's cigarette picking up sweetness from the bench [C112]. The regulatory fights began in earnest in 1969, when a rat study on the common cyclamate-saccharin mixture found bladder tumours; the United States banned cyclamate outright by 1970 and nearly banned saccharin in 1977, retreating only to a warning label that survived until 2000, when the rat-specific bladder mechanism behind the tumours was shown irrelevant to humans [C111, C112]. The split never healed: cyclamate remains prohibited in the United States while staying permitted in the European Union, and the current American roster is six approved intense sweeteners, saccharin, aspartame, acesulfame-K, sucralose, neotame and advantame, with stevia glycosides and monk fruit reaching the market through the GRAS route instead [C110, C112]. Yet the structural point stands. Intense sweeteners replace sweetness only. At the few-hundredths-of-the-weight doses their potency allows, they cannot on their own bulk a cake, set a jam, preserve a fruit or feed a yeast; a formulation can buy each function back ingredient by ingredient, as Chapter 21's ten-ingredient sugar-free preserve shows, but the work is then done by the other ingredients, not the sweetener [S29, S28, S-F21]. Their market position today, per S&P Global's 2025 industry abstract: cyclamate remains the highest-volume intense sweetener globally, saccharin and aspartame flat or declining in several regions, acesulfame-K, sucralose and stevia growing everywhere with sucralose fastest, stevia and monk fruit growing above average from still-small shares [C70].

The third family aims at the fortress itself: replacing bulk as well as sweetness. Its veterans are the polyol bulking agents of Chapter 21, which restore bulk at the price of a mandatory laxative warning [S-F21]; its newest contender is allulose, a monosaccharide epimer of fructose, differing only in the orientation of the hydroxyl group at the third carbon, C-3 [C130]. It is made by enzymatically converting fructose, which in at least one production process documented to regulators starts from sucrose itself, hydrolysed and isomerised: sugar rebuilt into its own rival [C130]. Its regulatory map is split wide open. In the United States it reached the market through the GRAS route, and the FDA's allulose guidance, issued in draft in 2019 and finalized in 2020, exercised enforcement discretion letting it stay out of the Total and Added Sugars label lines, counted at 0.4 calories per gram [C114, S-F5]. In the European Union it remained an unauthorised novel food as of mid-2025: EFSA's opinion that June, on an application pending since August 2018, concluded that safety "cannot be established" after the applicant repeatedly failed to supply requested data on identity, production and genotoxicity, a verdict on the dossier rather than a finding of harm [C130]. Whether a bulk replacement can scale is an open question; the answer will be written in regulatory dockets and production costs, not in taste tests.

The honest measure of the threat is the projection evidence: the OECD-FAO expects sugar to hold about 80 percent of caloric sweetener use through 2033, with intense sweeteners outside the caloric accounting entirely [S22]. The substitution threat that would truly move sugar demand is not a sweeter molecule but a behavioural or pharmaceutical shift in how much sweetness people want, which is why the GLP-1 question of Chapter 39 matters more than any sweetener launch. Sugar has been "about to be replaced" since saccharin in 1879; the curve in Chapter 20 records what happened instead. That is not an argument that replacement is impossible. It is a record of how hard the incumbent is to kill.

Chapter 39 - The demand future

After five centuries of almost unbroken growth, the question is no longer whether the world wants sugar but whether anything can slow it. The most authoritative projection available, the OECD-FAO Agricultural Outlook to 2033, answers carefully: growth continues, but it moves. Global sugar consumption is projected to expand at 1.2 percent a year, reaching 198 million tonnes by 2033, with average per-capita intake rising to 22.8 kilograms [S22]. Nearly all of that growth comes from Asia and Africa, which the Outlook projects to contribute 64 percent and 32 percent of world demand growth respectively, driven by urbanisation, rising incomes and the spread of processed food and drink [S22]. The rich world is a different story: per-capita consumption in the Americas, Europe and Oceania is projected to keep declining, slowly, under health pressure and policy [S22]. Europe is the only region projected to shrink in total [S22].

The arithmetic underneath those numbers is the oldest in the book. Sugar demand has always been driven less by taste, which is universal, than by purchasing power and food industry structure. Where incomes rise from low levels, calorie-dense packaged food and sweetened drinks are among the first things households buy more of, and the food industry meets that demand with products engineered around sugar's combined virtues: sweetness, bulk, preservation, texture and browning, all in one cheap ingredient (Chapter 21). The growth the Outlook projects is therefore not a forecast of changing tastes but of changing incomes and cities: the same transition Europe and North America completed in the nineteenth and twentieth centuries, now running across South Asia and Africa [S22]. The rich world's decline has the opposite mechanics. There sugar is no longer bought for calories but encountered as an ingredient, and the pressure points are its industrial uses: the reformulation that health taxes force (Chapter 36) removes sugar from products without asking the consumer to choose differently, which is why it works where exhortation fails.

India, soon to be the world's largest sugar consumer, shows the transition in one country's data. The USDA's New Delhi office forecasts Indian consumption at 31 million tonnes raw value in 2026/27, up 3 percent, but the composition matters more than the total: per-capita intake has stabilised at about 18 kilograms, commercial and institutional buyers - soft drinks, baked goods, confectionery, dairy, catering - now take 70 percent of consumption and keep expanding, while household use, the sugar bowl itself, declines gradually [C126]. And the health counter-current is already visible in the same market: with the world's second-largest diabetic population after China, India's affluent urban households are beginning to shift toward alternative sweeteners even as aggregate demand grows [C126]. That is the world's demand future in

miniature: totals rising on commercial use and incomes, per-person appetite flat, health pressure building at the top of the income ladder.

The near-term ledger sits under the projection. The USDA's Foreign Agricultural Service publishes the benchmark twice a year; its May 2026 edition forecast 2026/27 world production at 184.9 million tonnes: Brazil 42.5 million, India recovering to 33.6 million, the EU down to 14.4 million on shrinking beet area, Thailand 9.5 million, China 12.7 million, the United States 8.0 million, with world exports at 62.3 million [C92]. The same edition cut its own 2025/26 estimate by 3.2 million tonnes to 186.1 million, India's short crop revised down 5.3 million on excess rainfall, a live demonstration that even official crop numbers move [C92]. These are that report's published forecasts and estimates, not final outturns.

Sugar's dominance among caloric sweeteners is expected to hold. The Outlook projects sugar keeping about 80 percent of global caloric sweetener use through 2033, with high-fructose corn syrup stable around 8 percent and intense sweeteners outside the caloric accounting [S22]. The substitutes of Chapter 38 attack from the margins of a very large market.

Three genuine uncertainties hang over the projection, and honesty requires naming them. The first is health policy: taxes on sugar-sweetened beverages now cover much of the world (Chapter 36), and the evidence from Britain and Mexico shows they change what is sold and bought within a few years (Chapter 22) [S22, C29, C30, C131]. The second is ethanol: every tonne of cane diverted to fuel is a tonne not crystallised, and in Brazil and India the sugar market's future is partly a fuel-policy decision (Chapters 25, 27) [S22].

The third deserves its own paragraph, because it is the first genuinely new demand-side force in a century: the GLP-1 weight-loss drugs. Their clinical effect on appetite is established, and their spread has been fast enough that food companies now model it. What the drugs do to sugar demand specifically is a different question, and the best microeconomic evidence to date is more surprising than the headlines. A 2026 analysis of transaction-level grocery data from a large panel of American households, matching adopters against never-adopters, finds that starting a GLP-1 medication cuts the calories in a household's grocery purchases by 5.1 percent in the first half-year, with the effect then fading toward zero, and cuts grocery spending by 7.1 percent; the persistent cuts concentrate in meat and beans [C132]. The striking finding is what does not move: sugar and added sugar show no significant decline with adoption [C132]. The largest responses come from users of the weight-loss versions of the drugs, who cut calories 7.9 percent over the post-adoption horizon, against a statistically insignificant change for users of the diabetes versions [C132]. One household-panel study is not a forecast, and a drug class

this young has no long-run data at all. But the first careful evidence suggests the drugs shrink the grocery basket broadly rather than the sweet tooth specifically, which is why this book treats GLP-1 as a genuine open question rather than a scheduled obituary for sugar [C132, S22].

The projection machinery itself deserves a caveat. The Outlook is a model based on policy and price assumptions, not a prophecy: it assumes constant real oil prices and current policies, and its own authors list macroeconomic shocks, weather, and policy shifts as uncertainties that could move the numbers either way [S22]. The deepest fact in its favour is the five-century curve itself (Chapter 20): sugar demand has survived abolition, depression, beet, corn syrup, saccharin, aspartame and the obesity pandemic. The safe statement is the structural one. Sugar's demand future will be decided where most of the world's people live, in the growing cities of Asia and Africa, and by whether health policy and new medicines can bend a curve that nothing else has.

Chapter 40 - The technology frontier

Sugar's future will be built in three places: the field, the genome and the factory. Each has a live frontier, and each has an honest caveat.

In the field, precision agriculture is arriving at one of the world's most extensive crops: satellite and drone imagery, variable-rate application, harvest tracking, the full "Industry 4.0" stack, with adoption concentrated where farms are large and capital deep, Brazil's centre-south above all, and the documented gap between large and small producers widening accordingly [S23]. The pattern is familiar from every previous mechanisation in this book (Chapter 11): the technology rewards scale, and scale concentrates the industry. What is genuinely new is the information layer: a crop grown in ratoons over huge contiguous blocks generates the kind of repeatable, mappable data that precision tools exploit best, and a mill that knows its suppliers' fields block by block can schedule harvest against measured cane quality rather than calendar habit [S23].

In the genome, the tools have jumped a generation, and cane's peculiar biology decides the pace. Transgenic cane is no longer only experimental: Brazil's regulator listed eight approved events in its May 2024 table, all Bt borer resistance, all from one developer, CTC, and the first has been in commercial planting since the 2018/19 season [S-G2, S-G6]. Argentina has approved a glyphosate-tolerant event, field-tested from 2007 to 2014 in the cultivar RA 87-3, with a mandated herbicide-resistance stewardship plan and commercialization still a separate step that no source records as taken [S25, S-G3]. Indonesia has approved three drought-tolerant events for food use, not cultivation, a distinction that explains why the review literature counts only Brazil's releases as commercial [S25, S-G4]. Three countries, three different regulatory answers, and only one crop actually in the ground: the frontier is real, and narrower than the brochures suggest.

The reason the frontier moves slowly is the plant itself (Chapter 7). Cane's modern varieties are complex polyploid hybrids carrying a hundred-plus chromosomes from two ancestral species; they cannot be backcrossed the way simpler crops can, so every engineered variety must be transformed, selected and deregulated on its own, a process measured in decades per trait [S25]. Beyond insect resistance, disease, drought, sugar-content and biomass traits and CRISPR editing remain at trial stage, slowed by that same genome [S25]. Gene editing promises faster, more precise versions of the century-old breeding game of Chapter 7, but the promise runs ahead of the paperwork: a trait edited tomorrow would still face the deregulation queue that has kept Argentina's approved event unplanted [S25, S-G3]. The realistic reading is that

biotechnology will defend cane's yield frontier trait by trait rather than transform the crop at a stroke.

In the factory, the direction is the biorefinery of Chapter 26: sugar, ethanol, power, chemicals and materials from one stream of cane, with second-generation ethanol from bagasse and straw the largest single prize, technically proven, but with actual output still far below installed nameplates and the first wave of plants mostly shut or repurposed (Chapter 25) [S24, C116]. The cost trajectory underneath is genuinely encouraging: the review literature reports enzyme costs down from about two dollars to about thirty cents per gallon over a decade, its own figure hedged, while pretreatment of the fibre remains the most complex and costly stage [S24]. Nearer term, the unit machines keep moving: continuous crystallisers now sit alongside the century-old batch pan, and the distributed control system has become the plant's nervous system. One major automation vendor sells sugar-specific control libraries covering batch pans, continuous crystallisers, centrifuges, filters and falling-film evaporators [S-M22]; a 2020 open-access study examines automating diffuser control in a newer cane country [S-M26]. The vendor catalogues show what is offered, not what every factory runs, but the direction is plain: the same steam, the same cane, more crystal, less fuel, fewer operators. The next efficiency gains in sugar will come as much from control software as from new iron.

New sugars blur the line between sugar and substitute: allulose, a rare sugar occurring naturally in small amounts in raisins, dried figs and molasses and now also manufactured, is metabolised so little that in 2019 the US Food and Drug Administration moved to let it be excluded from the Total Sugars and Added Sugars lines of the nutrition label and counted at 0.4 calories per gram instead of the usual 4 [C114]. Chapter 38 follows its regulatory contest.

Each frontier has an honest caveat. Precision tools spread unevenly and can entrench scale [S23]. Commercial GM cane exists only in Brazil's Bt varieties, and nowhere else has cultivation been approved; the crop's genome makes each new engineered variety its own long deregulation [S25, S-G2]. The biorefinery's components all work somewhere and have not yet been assembled profitably everywhere [S24, S15]. The industry's research frontier is real and active; its history counsels patience with every "revolution" until the tonnes follow.

Chapter 41 - Bottlenecks

What could actually stop sugar? The industry's own evidence points to five constraints, and none of them is a substitute sweetener. Each is worth taking apart, because each binds in a different way and on a different clock.

Climate first. Cane's frost-free, water-fed envelope is moving, and weather shocks already disrupt output: the 2023-24 price rally was built on below-average rain in Brazil, India and Thailand, three of the four pillars of world supply, failing in the same season [S22]. A crop that takes a year or more to grow cannot answer a price signal inside the season that needs it, so every weather shock lands on the market at full force. The ratoon system that makes cane economical, several harvests from one planting, also spreads the exposure: a stressed stand does not reset with next year's planting the way an annual crop does, and replanting decisions made under drought or flood echo through several campaigns [S2b]. Beet's version of the exposure is the pest-regulation triangle documented in France in 2020, where a mild spring, an aphid infestation and a withdrawn seed treatment combined into a 30 to 50 percent yield loss estimate and an emergency policy reversal (Chapter 37) [C106, C107]. Neither industry can move its crop away from the weather; both can only breed, insure and lobby against it, each on a timescale slower than the shocks.

Water second. Cane is a heavy drinker even by crop standards, with the seasonal demand Chapter 9 numbers, met by rain where rain obliges and increasingly by irrigation where it does not [S-C1, S2b]. Irrigation puts sugar into direct competition with cities and other crops for a resource that is itself under climate pressure, and the competition is visible in the industry's own geography: the expansion frontiers of the twentieth century ran on new water as much as on new land [S2b]. The French engineers of eighteenth-century Saint-Domingue were already building reservoirs and aqueducts to push cane onto drier plains (Chapter 6); the constraint is as old as the plantation, but the competition for the water is new. As watershed accounts tighten, the industry will increasingly be asked to prove its water accounts the way it now must prove its carbon ones.

Perishability and concentration third. Cane must be crushed within hours of cutting, which ties every hectare of supply to mill capacity within trucking distance - the reason the mill, not the field, sets the scale of the enterprise (Chapter 6). That is the oldest bottleneck in the industry and the least fixable: it is written into the plant's chemistry, and every logistical system in Chapter 33 exists to manage it. On the export side the concentration is starker still: half of world trade comes from one country, which makes the world market hostage to one nation's weather, cane-versus-ethanol choices and export policy [S22].

Chapter 32 follows what that does to everyone else's planning. Concentration is the industry's efficiency and its fragility in the same fact: the centre-south's mills, railways and Santos terminals are the cheapest route from cane to consumer ever built, and a single season's failure there is a world market event.

Genetics fourth. The narrow clonal base of modern cane (Chapter 7) is a standing invitation to a disease event with no resistant varieties in reserve; the industry's history of rescue-by-new-variety, from the noble canes through the POJ hybrids, is a history of a bottleneck escaped, not removed [S2b, S39]. What has changed is the toolbox and its speed: biotechnology can now build resistance directly, but deregulation runs on a political clock far slower than a breeding cycle, as Chapter 40's three-country map of approved and unplanted varieties shows [S25, S-G3]. The genetic bottleneck is thus really two: biology's, which science can now answer, and regulation's, which science cannot.

Policy fifth. Sugar is among the most governed foods on earth - taxed, quota'd, subsidised and mandated - and a coordinated policy turn, on health or on trade, could move demand faster than any agronomic change [S16, C45]. At least 108 countries taxed sugar-sweetened beverages as of 2022, a count that would have been unimaginable in 2010 [S16]. Unlike the other four constraints, this one can bind within a single parliamentary term.

The constraints are not abstractions; two documented cases show their working teeth. In Indonesia, thirty-seven of the forty-three state-owned sugar mills are over a century old, the industry's average five-year recovery rate ran at just 7.1 percent in 2025/26, and modern refineries sat starved not of demand but of state-rationed raw-sugar import permits (Chapter 28) - capacity, age and policy binding at once [C76]. In Queensland, the bottleneck was control of the only route to sea: the fight over who operates the industry's six bulk terminals, settled on 1 July 2026 as Chapter 33 records, leaves the deeper question - who commands chokepoint infrastructure, and on whose terms - to outlive the settlement [C23, C23b].

These constraints interact, which is why they matter more together than separately: a climate shock in a concentrated-export system meets a thin genetic base and a policy environment already taxing the product. The industry's history says it adapts; the industry's science says the adaptation must now run faster than the breeding cycle that has always saved it before [S39].

Chapter 42 - The connected industries

Every industry this book has touched is a door into another investigation. This chapter is the registry: each connected industry named once, its role in sugar's story stated, and its case for its own deep investigation assessed. It is deliberately a map, not a summary.

Ethanol and fuel. Sugar's largest non-food outlet (Chapter 25), and the industry with the strongest claim to a book of its own: Brazil's Proalcool, launched in 1975 after the oil crisis made imported fuel a strategic vulnerability, built a complete system of guaranteed prices, credit lines and state cane-breeding for fuel, and every blending mandate since has been written in its shadow [S32]. The fuel question is never far from the sugar question, because the same mills choose between them season by season.

Rum and distilling. Molasses's oldest industry (Chapter 24) and a spirits business in its own right, still concentrated where the cane grows and still fed principally on blackstrap, the final molasses after repeated boiling [C35]. Because its feedstock is the refinery's residue, rum economics is a branch of molasses economics - and molasses, as Part VIII records, is now a technology choice.

Confectionery and chocolate. Sugar as structural material (Chapter 21): the chocolate industry is sugar-plus-cacao economics in its own right, and its reformulation frontier is a research programme of its own [S29].

Soft drinks. Sugar's largest industrial customer (Chapter 22) and the front line of health policy (Chapter 36). Industrial use of sugar is where consumption growth has concentrated, and soft-drink manufacturing has grown fastest of all [S30] - which is why the drinks aisle is where the taxes landed first [S16].

Industrial fermentation. Citric acid, yeast, amino acids and the antibiotics feedstock chain (Chapter 23). The landmark case is Pfizer's SUCIAC process - "Sugar Under Conversion to Citric Acid" - which grew Aspergillus mould on sucrose and turned a substance once squeezed from lemons into a bulk industrial chemical; the deep-tank fermentation engineering perfected on sugar-fed processes then made penicillin possible at wartime scale, a technology lineage that runs from the sugar economy to the antibiotic era [S40].

Sugar machinery. The specialist engineering trade of Part VI, from Glasgow's cluster through Derosne and Cail to BMA and Buckau-Wolf [S-M4, S-M14]. This investigation found the industry's own archive barely touched by general historians; the case for a dedicated volume is already made.

Bulk shipping and port terminals. Chapter 33's bulk terminals and the stevedoring systems behind them: raw sugar moves as a flowing bulk solid in purpose-built systems, and the terminals that load it are chokepoint infrastructure, as Queensland's long contest over its six industry-owned terminals showed [C23, C23b].

Commodity exchanges. Chapter 30's two-contract world and its lineage from the nineteenth-century coffee exchange to today's ICE futures [E7]. The exchange is where sugar became a price as well as a product.

Irrigation systems. Cane's water infrastructure (Chapter 9), the unglamorous engineering on which the tropical half of the industry stands [S2b]. Bagasse paper and board. Chapter 26's materials branch, where the fibre that once only fuelled the boiler became a product [S2b].

Two selection principles govern what deserves its own investigation. Strength of connection: industries that exist because sugar exists (machinery, rum, HFCS's mirror industry) outrank industries sugar merely supplies. And evidence depth: where this investigation uncovered rich untouched material, as in machinery, cane railways and refining dynasties, the case for a dedicated volume is already made. The order suggested: sugar machinery first, then the economies volumes, then downstream food industries, mirroring the structure this book itself validated.

Chapter 43 - Conclusion: the long arc

This book began with a molecule and closes at the edge of an open market, and the argument of every chapter between them is that the two were never separate. Sucrose is one glucose joined to one fructose; everything else, the plantations and the mills, the ships and the futures contracts, the duties and the quotas and the taxes, is what human beings built around the fact that a grass could concentrate that molecule better than almost anything else alive, and that nearly everyone who tastes it wants more.

Look back down the arc and a small number of mechanisms do nearly all the work. The first is the crop's perishability. Cut cane spoils within days, so the factory had to stand beside the field, and the factory's cost demanded scale, and scale demanded a disciplined, enormous labour force. None of that dictated how the labour would be found. The Atlantic world's answer was coercion - a political and institutional choice, made by merchants, planters and parliaments, not a necessity secreted by the molecule. Around that choice grew the plantation complex, the Atlantic slave trade's largest destination, the indenture system that followed emancipation, and the particular shapes of a dozen economies from Barbados to Fiji. Crop perishability and factory capital shaped the pressures the industry worked under; political institutions, property regimes and power determined how its labour was organised, and coerced. That the coercion was a choice, and whose choice it was, is the bleakest sentence this book has had to write.

The second mechanism is the machine. Crystallisation turned a sap into a commodity; the vacuum pan, the multiple-effect evaporator, the centrifuge and the diffuser turned the commodity into an industry; and a specialist engineering trade, Glasgow to Magdeburg to Sao Paulo, arose to build it all. Machines decided who could compete: the beet factory against the tropical estate, the central mill against the smallholder, the refiner against the planter. Every chapter of the industrial story is a chapter about where the margin moved when a new machine arrived.

The third is the state. Sugar has been taxed, quotaed, preferenced and protected for most of its commercial history. Duties built fortunes and provoked a revolution; quotas and preference regimes decided which islands could live by cane and which could not; the American programme still walls its market off at two or three times the world price; and the newest instrument, the sugar tax, aims at demand itself rather than supply. Sugar's price has never been only a price. It is a political decision wearing a number.

The fourth is the one the future chapters rest on: arithmetic. Five centuries of demand growth have survived abolition, depression, beet sugar, corn syrup,

saccharin, aspartame and the obesity pandemic, because the things that make people want sugar, price, habit, and the food industry's appetite for a cheap, functional ingredient, have always outweighed the things that warn them off it. The current projections continue the curve: slower growth, moving south and east, with the rich world's per-capita appetite slowly falling and the poor world's still rising. Health policy and the new weight-loss drugs press on demand itself, a side of the ledger that has rarely been pressed before. Whether they bend the curve where nothing else has is the open question with which the demand chapter honestly ends.

And the constraints are gathering on the supply side at the same time: a climatic envelope on the move, water accounts that no longer balance in every region, a genetic base still narrower than the industry's history of rescue-by-new-variety makes comfortable, and half of world trade dependent on one country's weather and fuel policy. Each of these has a precedent the industry survived. Their combination, arriving together with serious demand-side pressure, does not.

So the honest closing is not a prediction but a pattern. Sugar has been pronounced finished many times: when slavery ended, when beet undercut cane, when corn syrup took the American soft drink, when medicine turned against it. Each time the industry adapted, moved, concentrated, lobbied, engineered, and the curve went on rising. That record is not a guarantee; it is a description of an incumbent with extraordinary resilience built from chemistry, capital and political protection. The next fifty years will test all three at once. If the curve finally bends, the bend will begin where this book's story has always lived: in the meeting of a plant, a price and a political decision.

What sugar leaves behind, either way, is already written. It organised the early modern world as few commodities ever have: it drew the maps of the Caribbean and the Indian Ocean, moved millions of people against their will and millions more by contract, built ports, railways, refineries, trading houses and fortunes, fed the fiscal machinery of states, and taught the world to eat sweetness every day. The industry that remains is smaller than that empire but still immense, still governed, still contested, and still, at bottom, a grass, a crystal, and an appetite. The molecule has not changed in five centuries. Everything built around it never stops changing. That is the whole story, and it is not over.

Chapter 44 - A sugar glossary

The working vocabulary of the book, in one place. Terms are defined as the industry uses them; chapter numbers point to the fuller treatment.

BAGASSE. The crushed fibre left after cane is milled; the factory's boiler fuel and the raw material of the biorefinery. (Chapter 26)

BRIX. A measure of dissolved solids, effectively sugar concentration, in juice or syrup. (Chapter 13)

CENTRIFUGE. The spinning basket that flings molasses off the crystals; the machine that made white sugar an industrial product. (Chapter 15)

COSSETTES. The thin slices cut from sugar beet for diffusion. (Chapter 10)

DIFFUSION. Extraction by washing, hot water percolating through prepared cane or cossettes, against the flow; the rival of milling. (Chapter 13)

ENGENHO. The Portuguese colonial sugar estate and its mill; the social atom of early Brazil. (Chapter 35)

FIRST STRIKE. The highest-grade crystals from the first crystallisation of a syrup; raw-sugar manufacture's first cut. (Chapter 15)

GREEN CANE. Cane harvested without burning, with its leafy trash left on the field; the growing environmental standard. (Chapter 11)

IMBIBITION. Water sprayed against the cane flow in a milling tandem to wash out residual sugar. (Chapter 13)

INVERSION. The splitting of sucrose into glucose and fructose; the product is invert syrup, and the reaction is why jam sets differently from syrup. (Chapter 21)

MAGMA. A paste of crystals and syrup re-mingled for a further strike. (Chapter 15)

JAVA RATIO. The mill's check figure: the cane's pol content set against the pol of the first expressed juice, a simple indirect measure of cane quality. (Chapter 13)

MASSECUITE. The mixed mass of crystals and mother syrup that comes out of a vacuum pan, "cooked mass" in the industry's French. (Chapter 15)

MOLASSES. The syrup that no longer yields crystals economically; feedstock for rum, yeast and industry. (Chapter 24)

MULTIPLE EFFECT. Evaporating in stages, each stage heated by the vapour of the one before; Rillieux's principle, covered by United States patents of 1843

and 1846 and first commissioned in 1843. (Chapter 14)

POLARISATION. The measure of sucrose content by optical rotation; the trade's grading number, from 96 degrees raw to 99.8 refined. (Chapters 16, 30)

RAWS. Bulk brown sugar, polarisation around 96 degrees, the main commodity traded internationally. (Chapter 32)

PURITY. The share of dissolved solids that is actually sucrose, rising from 80-something percent in mixed juice to near 100 in refined liquor. (Chapter 14)

REFINING. Dissolving raws, clarifying and decolourising the liquor, and re-crystallising to white; the port-city business. (Chapter 16)

STRIKE. One batch boiled in a vacuum pan. (Chapter 15)

SUCROSE. The molecule itself, C12H22O11, one glucose joined to one fructose. (Chapter 1)

TRASH. Cane leaves and tops, burned before harvest or left on the soil as blanket. (Chapter 11)

VACUUM PAN. The closed, reduced-pressure vessel in which syrup is boiled into massecuite without scorching; Howard's 1813 patent, disputed by one year. (Chapter 14)

WHITES. Refined sugar, 99.8 degrees polarisation and above. (Chapter 32)

ZAFRA. The Spanish-speaking world's word for the cane harvest and crushing season. (Chapter 11)