SECTION I
PRACTICAL CHEMISTRY: MINING, METALLURGY, AND WAR

THE BIRTH OF METALS

What does this allegorical figure (Figure 1) represent? This bald, muscular figure has the symbols of seven original elements arrayed around (and likely including) the head. The all-too-perfect roundness of the head appears to correspond to the perfect circle that represents gold. The unique positions of male (sun) and female (moon) suggest the birth of metals.[1]

The elements, also including antimony and sulfur, are also buried in the intestines of the figure—literally its bowels—and now we have a hint of its nature. Any attempts at further interpretation are in the realm of psychology rather than science, and indeed the famous psychologist C.G. Jung owned a valuable collection of alchemical books and manuscripts and wrote extensively on the subject.[2]

At its heart, alchemy postulated a fundamental matter or state, the *Prima Materia,* the basis for formation of all substances. The definitions[2] of the *Prima Materia* are broad, partly chemical, partly mythological: quicksilver, iron, gold, lead, salt, sulfur, water, air, fire, earth, mother, moon, dragon, dew. At a more philosophical level, it has been defined as Hades as well as Earth.[2] Another figure from a seventeenth-century book on alchemy was identified by Jung as the *Prima Materia*—a similar muscular Earth shown suckling the "son of the philosophers."[2] This figure also has the breasts of a woman; the hermaphroditic being is reminiscent of the derivation of Eve from Adam and the subsequent seeding of the human species. The hermaphrodite is greater than the sum of its male and female natures.

Let us cling to the Earth analogy because it seems to help in understanding the presence of the elements in its bowels. The small figure in the upper abdomen, the homunculus, may be considered to be a type of Earth Spirit nurturing the growth of living things (see vegetation below it) and "multiplication" of the metals. The unique positions of gold (the head as well as the highest level in the intestines) implies *transmutation*—the conversion of base metals into noble metals. The figure holds a harp, representing harmony, and an isosceles triangle, representing symmetry. It is a metaphor for the unity that the true alchemists perceived between their art and nature.

This plate is the frontispiece from the book *Physica Subterranea* published by the German chemist and physician Georg Ernst Stahl in 1738.[3] It is the last edition of the famous book published by Johann Joachim Becher in 1669. Becher evolved chemistry's first unifying theory, the Phlogiston Theory, from alchemical concepts and it was subsequently made useful by Stahl. So in this plate are themes of alchemical transmutation, spiritual beliefs, and early chemical science that will begin our tour of alchemy and chemistry over two thousand years.

From Alchemy to Chemistry in Picture and Story. By Arthur Greenberg.

FIGURE 1. ■ Frontispiece from the final edition of *Physica Subterranea* by Johann Joachim Becher (Leipzig, 1738). The hermaphroditic figure may represent the Primary Matter (*Prima Materia*). The dwarf-like figure inside the body is the homunculus, the offspring of the "chymical wedding."

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1. A. Roob, *The Hermetic Museum: Alchemy & Mysticism*, Benedikt Taschen Verlag GmbH, 1997, p. 183.

2. N. Schwartz-Salant, *Jung on Alchemy,* Princeton University Press, Princeton, NJ, 1995, pp. 25–30; 44–49.
3. A different interpretation of this figure, namely as Saturn, is to be found in C.A. Reichen, *A History of Chemistry,* Hawthorne Books, New York, 1963, p. 8.

THE ESSENCE OF MATTER: FOUR ELEMENTS (OR FIVE): THREE PRINCIPLES (OR TWO) OR THREE SUBATOMIC PARTICLES (OR MORE)

The ancient Greek philosophers were not scientists. They were, however, original thinkers who attempted to explain nature on a logical basis rather than by the whims of gods and goddesses. The father of this movement is considered to be Thales of Miletus, and during the sixth century B.C., he conceived of water as the essence of all matter. (We note later in this book that, in the mid-seventeeth century, Van Helmont had a somewhat similar view.) Thales is reputed to have predicted the total solar eclipse of 585 B.C., said to have occurred during a naval battle—although there is no basis for him having the knowledge to make such a prediction.[1] One of his successors in the Milesian School was Empedocles of Agrigentum (ca. 490–430 B.C.).[1] Empedocles is said to be the first to propose that all matter is composed of four primordial elements of equal importance,[2,3] although similar ideas appear to have formed in Egypt, India, and China (five elements) around 1500 B.C.[2] Figure 2 depicts the four earthly elements. It appears in *De Responsione Mundi et Astrorum Ordinatione* (Augsburg, 1472), a book derived from the writings of Saint Isidorus, Bishop of Seville, during the seventh century A.D.[4]

Although Empedocles wrote about the actual physical structure of matter, it was only during the fifth century B.C. that two philosophers of the Milesian School enunciated a coherent atomic cosmology. None of the writings of Leuccipus remain, but he is widely accepted as real and some of the writings of Democritus (ca. 460–ca. 370 B.C.),[1] his student, are known. For these scholars there were two realities in nature: Atoms (*atomos*, meaning not cuttable) and Void (derived from *vacuus*, meaning empty).[3] Void was considered to be as real as Atoms. Atoms of water were thought to be smooth and slippery; those of iron were jagged with hooks.

Aristotle (384–322 B.C.) is considered to be one of the two greatest thinkers of ancient times, the other being Plato.[1] Aristotle proposed a kind of primordial, heavenly element, "ether," and to each of the four earthly elements attributed two pairs of opposite or contrary "qualities" (wet versus dry; hot versus cold). The relationships between the elements and their qualities are depicted in a square that nicely places contrary qualities on opposite edges. The square is one of the fundamental symbols that often appear in alchemical manuscripts and books even as late as the eighteenth century. Thus, a liquid (rich in water) is cold and wet while its vapor (rich in air) is hot and wet. To vaporize a liquid, simply add heat—move from the cold edge to the hot edge of the square. To dissolve a solid (rich in earth), add wet; to burn the solid, add hot. Fire was not solid, liquid, or gas but a form of internal energy—perhaps related to the eighteenth-century concept of "caloric" propounded by Lavoisier.[2]

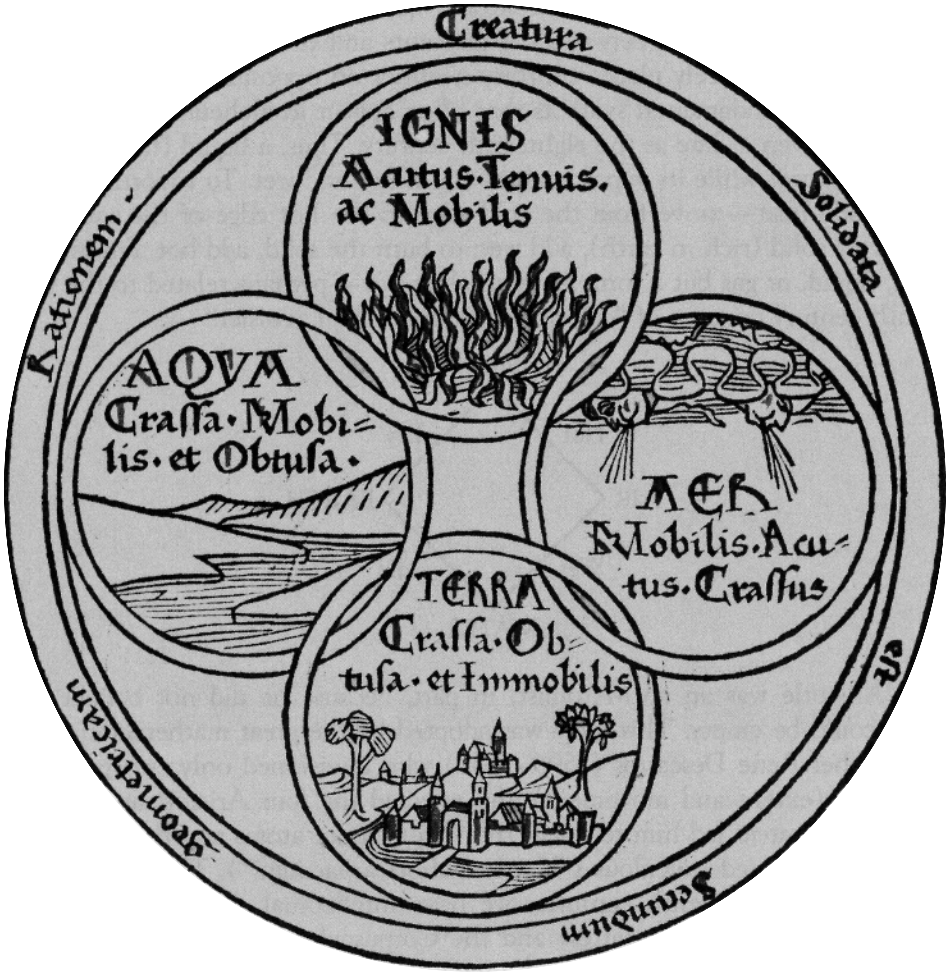
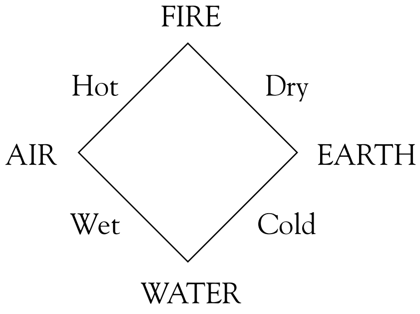


FIGURE 2. ■ The four elements of the ancients: Fire, Air, Earth, and Water from St. Isidore, *De Responsione Mundi Et Astrorum Ordinatione* (Augsburg, 1472) (courtesy of The Beinecke Rare Book and Manuscript Library, Yale University).



Aristotle was an anti-Atomist, in part, because he did not believe that space could be empty. This view was adopted by the great mathematician and philosopher Rene Descartes (1596–1650) who envisioned only two principles in matter (extent and movement) and rejected the four Aristotlean qualities. The idea of extent led him to reject the idea of finite atoms and the concept of void he considered ridiculous ("Nature abhors a vacuum"[5]). Thus, in the seventeenth and eighteenth centuries we have intellectual conflict between the Cartesians (school of Descartes) and the Corpuscular school (corpuscles were similar, yet fundamentally different, in concept to atoms), which included Robert Boyle and Isaac Newton.[6]

A 1747 oil-on-wood painting signed by a Johann Winckler[7] (Figure 3) joyously employs alchemical, spiritual, and religious symbolism characteristic of Rosicrucian beliefs. Most prominent are the four abbots whose activities symbolize earth, fire, air, and water. They are arrayed in the appropriate order of contrary properties—cold versus hot; wet versus dry.

The Cupid (or Mercurious) figure was said by the psychologist Carl Jung to represent "the archer who, chemically, dissolves the gold, and morally, pierces the soul with the dart of passion."[8] "Christian Rosencreutz in *The Chymical Wedding* is pricked with a dart by Cupid after stumbling upon the naked Venus."[8] The four abbots and the Venus figure each possess a vessel containing the Red Tincture, which represents the transmuting agent or Philosopher's Stone[9] or a preliminary stage of the Stone.[10] The castles may represent . . . well . . . castles. Or . . . they may symbolize the athanor or philosopher's furnace, which holds the hermetically sealed philosopher's egg.[11] The pair of doves represent the *albedo*, the white color that follows the *nigredo*, or the initial black color of The Great Work. Initially, metals and other substances are heated to form a black mass. Subsequent heating may calcine this mass to produce a white calx. Now, if that long-tailed bird attached to an abbot by a string is a peacock, we see represented the third color change of The Great Work, the rainbow hues. The fourth and final color is the ruby of the Red Tincture—four cucurbits—full and one goblets-worth in this painting. The phoenix also represents this final ruby red color but no phoenix is seen rising (or expiring) in the painting. No crows are in evidence either, so let's assume that the coals or the ashes in the athanor represent the *nigredo*.

Rosicrucians combine religious, occult, and alchemical beliefs.[12] Although the earliest writings date to the beginning of the seventeenth century, the origins of Rosicrucianism are commonly attributed to a Christian Rosenkreutz ("rosy cross"), allegedly born in 1378. Some consider the early sixteenth-century physician and alchemist Paracelsus to be the true founder. The alchemist Michael Maier appears to have been a Rosicrucian.[13]

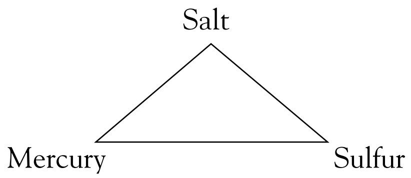
The sign in the lower right of this painting may be translated as follows:

1. I search in the water here.
2. The air should give me
3. I search in the earth
4. The fires should become for me
5. Something here, you fools, here in the water, air and earths.
   In the fire, shall you busily search.
6. All here suddenly becomes.

During the Renaissance, the classical Greek views of nature were finally challenged by the likes of Paracelsus.[14] Paracelsus extended an earlier view of matter that held that it was a union between an exalted sulfur of the philosophers ("Sophic Sulfur"—characterized often as male) and an exalted mercury of

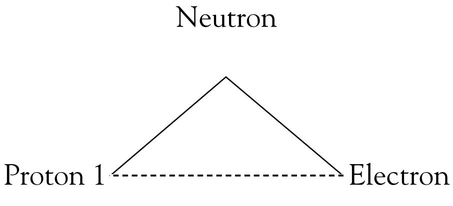
FIGURE 3. ■ Eighteenth-century painting by a Johann Winckler, exhibiting Rosicrucian influences, in which the four friars represent water, air, fire, and earth in a correctly ordered square. The red tincture (see color plates) in the possession of each friar, is an embodiment of the Philosopher's Stone—the mysterious agent of projection and transmutation.

the philosophers ("Sophic Mercury"—characterized often as female). These are not related to the chemical elements we now recognize as sulfur and mercury. To these Paracelsus added Salt as the third Principle. Now, Mercury is Spirit, Sulfur is Soul, and Salt is Material Body. The relationship is depicted as a triangle, the other great metaphor found in alchemical manuscripts and books



through the eighteenth century. All matter is composed of these three principles in various proportions. Later in this book (Figure 96) we see two such symbolic triangles in Oswald Croll's *Basilica Chymica*. Croll presented Paracelsan alchemy—the bottom triangle presents Life, Spirit, Body (or Fire, Air, Water or Animal, Vegetable, Mineral). Symbols of triangles and squares abound in alchemy. The Sioux view the circle as their high ideal: "circle of Life," the tipi, the campfire.[15] In his nineteenth-century satire *Flatland*, Edwin Abbot portrays increasing perfection through each successive generation as a triangle begets a square, which begets a pentagon, and so on. A *megagon* is close to the perfection of a circle—a kind of generational transmutation.

The modern view of the atom is that it *is* divisible and that the fundamental particles making up all atoms of all elements are protons (positive charge), neutrons (zero charge), in an unimaginably dense nucleus occupying a miniscule fraction of the atom's volume, and electrons (negative charge).[16] The positive nucleus and the negative electrons are our modern "contraries." (Incidentally, it was Benjamin Franklin who introduced the negative–positive nomenclature in the context of electricity.[17]) The electrons are considered to be fundamental particles of infinite lifetime and are actually one of six subatomic particles called leptons. Protons and neutrons are not considered fundamental and are two of a very complex class of subatomic particles called hadrons. Outside of the nucleus, a free neutron has a half-life of only 17 minutes and decays into a proton, an electron (β particle), and an antineutrino—another lepton.[16] So, based upon this modern view, we can draw a Paracelsan-style triangle, but not equilateral in the sense that the neutron can give rise to the other two. The modern *Prima Materia* could be a dense neutron star.



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1. *Encyclopedia Brittanica,* 15th ed. Vol. 11, Chicago, 1986, p. 670.
2. J. Read, *Prelude to Chemistry,* MacMillan, New York, 1937, pp. 8–11.

3. B. Pullman, *The Atom in the History of Human Thought*, Oxford University Press, New York, 1998, pp. 2–47.
4. I. MacPhail, *Alchemy and The Occult*, Yale University Library, New Haven, 1968, Vol. 1, pp. 3–4.
5. Two sources for quotations simply refer this phrase (*Natura abhorret vacuum*) to a Latin proverb [B. Evans, *Dictionary of Quotations*, Delacorte Press, New York, 1968, p. 720, and *Dictionary of Foreign Quotations*, R. Collison and M. Collison (eds.), Facts on File, New York, 1980, p. 241]. One source attributes it to Gargantua in 1534 but from an ancient Latin source [A. Partington (ed.), *The Oxford Dictionary of Quotations*, 4th ed., Oxford University Press, New York, 1992, p. 534; *Bartlett's Familiar Quotations*, 16th ed., J. Kaplan (ed.), Little, Brown, Boston, 1992, p. 277] attributes the phrase to Spinoza in 1677. Just thought you'd want to know this one for the next Happy Hour.
6. B. Pullman, op. cit., pp. 140–142, 157–163.
7. I am not certain about the identity of the artist. One possibility is Johann Heinrich Winckler (1703–1770).
8. L. Abraham, *A Dictionary of Alchemical Imagery*, Cambridge University Press, Cambridge, UK, 1998, p. 51.
9. J. Read, op. cit., p. 12; p. 148.
10. Abraham, op. cit., p. 169.
11. Abraham, op. cit., pp. 31–32.
12. *The New Encyclopedia Britannica*, Encyclopedia Britannica, Inc., Chicago, 1986, Vol. 10, p. 188.
13. Read, op. cit., pp. 230–232.
14. J. Read, op. cit., pp. 21–30.
15. J. Lame Deer and R. Erdoes, *Lame Deer Seeker of Visions*, Simon and Schuster, New York, 1972, pp. 108–118.
16. B. Pullman, op. cit., pp. 343–353.
17. J.R. Partington, *A History of Chemistry*, MacMillan, London, 1962, Vol. 3, p. 66.

UNIFYING THE INFINITE AND THE INFINITESIMAL

It is human nature to try to harmonize our universe—to attempt to unify the infinite with the infinitesimal. Pythagoras and his followers developed a purely mathematical conception of the universe. As Pullman notes:[1] "Indeed, the Pythagoreans held that numbers are the essence of all things. Numbers are the source of what is real; they themselves constitute the things of the world."

Mendeleev developed the periodic table roughly 2400 years after Pythagoras died. He could not possibly have understood the origin of its order. But in 1926, the new quantum mechanics of Schrödinger explained the periodic table on the simple basis of four quantum numbers (n, l, m, and s) that students now learn in high school. Pythagoras would have been pleased but not surprised.

Figure 4 is from Johannes Kepler's *Harmonices Mundi* (1619). The fanciful drawings on the middle right depict the five platonic solids—polyhedra whose faces are uniformly composed of triangles, squares, or pentagons. The Pythagorean Philolaus of Tarentum (480 B.C.–?) is generally credited with equating the four earthly elements to these polyhedra.[1] Starting from the top center and moving counterclockwise, we have the tetrahedron (fire), octahedron (air), cube (earth), and icosahedron (water). Plato added the fifth solid, the dodecahedron,

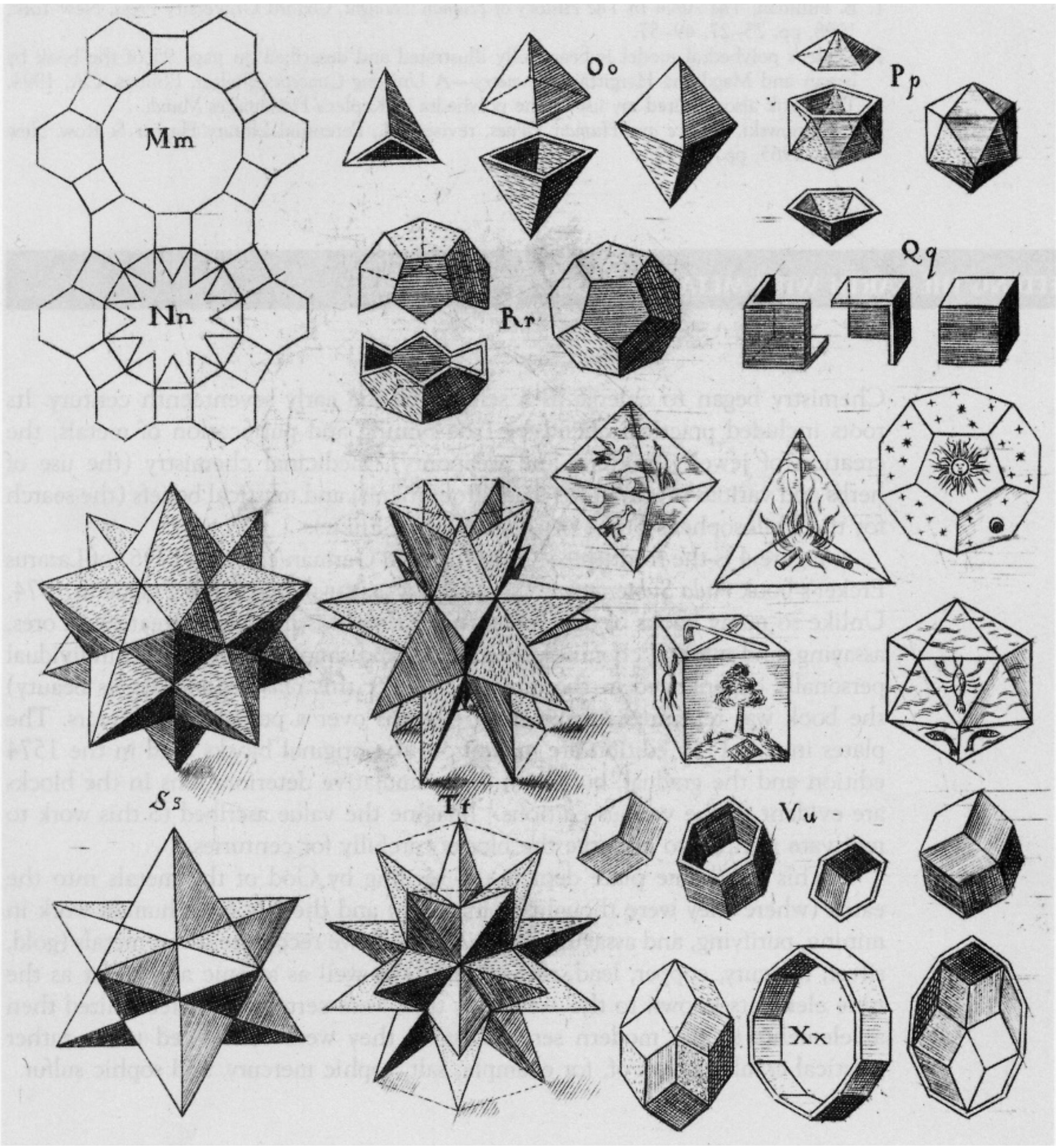

FIGURE 4. ■ Polyhedra in Johannes Kepler's *Harmonices Mundi* (Linz, 1619). Note the five Platonic solids on the middle right of this figure representing the four earthly elements Air, Fire, Water, and Earth as well as the fifth (heavenly) element Ether (courtesy of Division of Rare and Manuscript Collection, Carl A. Kroch Library, Cornell University).

to represent the universe (similar to Aristotle's ether). The tetrahedron is the sharpest of these polyhedra, and fire is, thus, the "most penetrating" element. The dodecahedron is most sphere-like, most perfect. Its pentagons are also unique—you cannot tile a floor with pentagons as you can with triangles, squares, and hexagons. Plato further imagined that the four earthly elements were themselves composed of fundamental triangles—an isosceles right triangle

A (derived from halving the square face of the cube) and a right-triangle B (derived from halving the equilateral triangular face of the tetrahedron, octahedron, or icosahedron). Earth was composed of triangle A. Air, fire, and water were composed of triangle B and could therefore be interconverted.[1]

In his 1596 book *Mysterium Cosmographicum*, Kepler proposed a solar system that placed the orbits of the six known planets on concentric spheres inscribed within and circumscribed on these five polyhedra arranged concentrically.[2] In the words of Jacob Bronowski:[3] "All science is the search for unity in hidden likenesses." He states further: "To us, the analogies by which Kepler listened for the movement of the planets in the music of the spheres are farfetched. Yet are they more so than the wild leap by which Rutherford and Bohr in our own century found a model for the atom in, of all places, the planetary system?"

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1. B. Pullman, *The Atom In The History of Human Thought*, Oxford University Press, New York, 1998, pp. 25–27, 49–57.
2. Kepler's polyhedral model is beautifully illustrated and described on page 95 of the book by Istvan and Magdolna Hargittai, *Symmetry—A Unifying Concept*, Shelter, Bolinas, CA, 1994. This book also inspired my use of the polyhedra in Kepler's *Harmonices Mundi*.
3. J. Bronowski, *Science and Human Values*, revised ed., Perennial Library Harper & Row, New York, 1965, pp.12–13.

SEEDING THE EARTH WITH METALS

Chemistry began to emerge as a science in the early seventeenth century. Its roots included practical chemistry (the mining and purification of metals, the creation of jewelry, pottery, and weaponry), medicinal chemistry (the use of herbs and various preparations made from them), and mystical beliefs (the search for the Philosopher's Stone or the Universal Elixir).

Figure 5 is the frontispiece from the final German edition (1736) of Lazarus Ercker's book *Aula Subterranea* . . . , which was first published in Prague in 1574. Unlike so many books of the sixteenth century, this important treatise on ores, assaying, and mineral chemistry was clearly and simply written by an individual personally experienced in the mining arts. For this reason (and for its beauty) the book was reprinted in numerous editions over a period of 160 years. The plates in this 1736 edition are made from the original blocks used in the 1574 edition and the gradual, but slight and cumulative deteriorations in the blocks are evident in the various editions.[1] Imagine the value ascribed to this work to motivate printers to preserve the blocks carefully for centuries.

This handsome plate depicts the seeding by God of the metals inside the earth (only there can they multiply naturally) and the laborious human work in mining, purifying, and assaying them. The heat inside the Earth is singular in its nature with no counterpart on the surface. Although we recognize seven metals (gold, silver, mercury, copper, lead, tin, and iron) as well as arsenic and sulfur as the nine elements known to the Ancients, they were certainly not recognized then as elements in the modern sense. Instead they were considered to

FIGURE 5. ■ Frontispiece from the final edition of *Aula Subterranea* by Lazarus Ercker (Frankfurt, 1736) depicting God seeding the earth with metals and their harvesting and refining by people. (The first edition of this book was published in 1574; the original blocks were employed to strike the plates in all subsequent editions.)

be rather mystical combinations of, for example, salt, sophic mercury, and sophic sulfur.

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1. A.G. Sisco and C.S. Smith, *Lazarus Ercker's Treatise on Ores and Assaying* (translated from the German Edition of 1580), The University of Chicago Press, Chicago, 1951.

CHYMICALL CHARACTERS

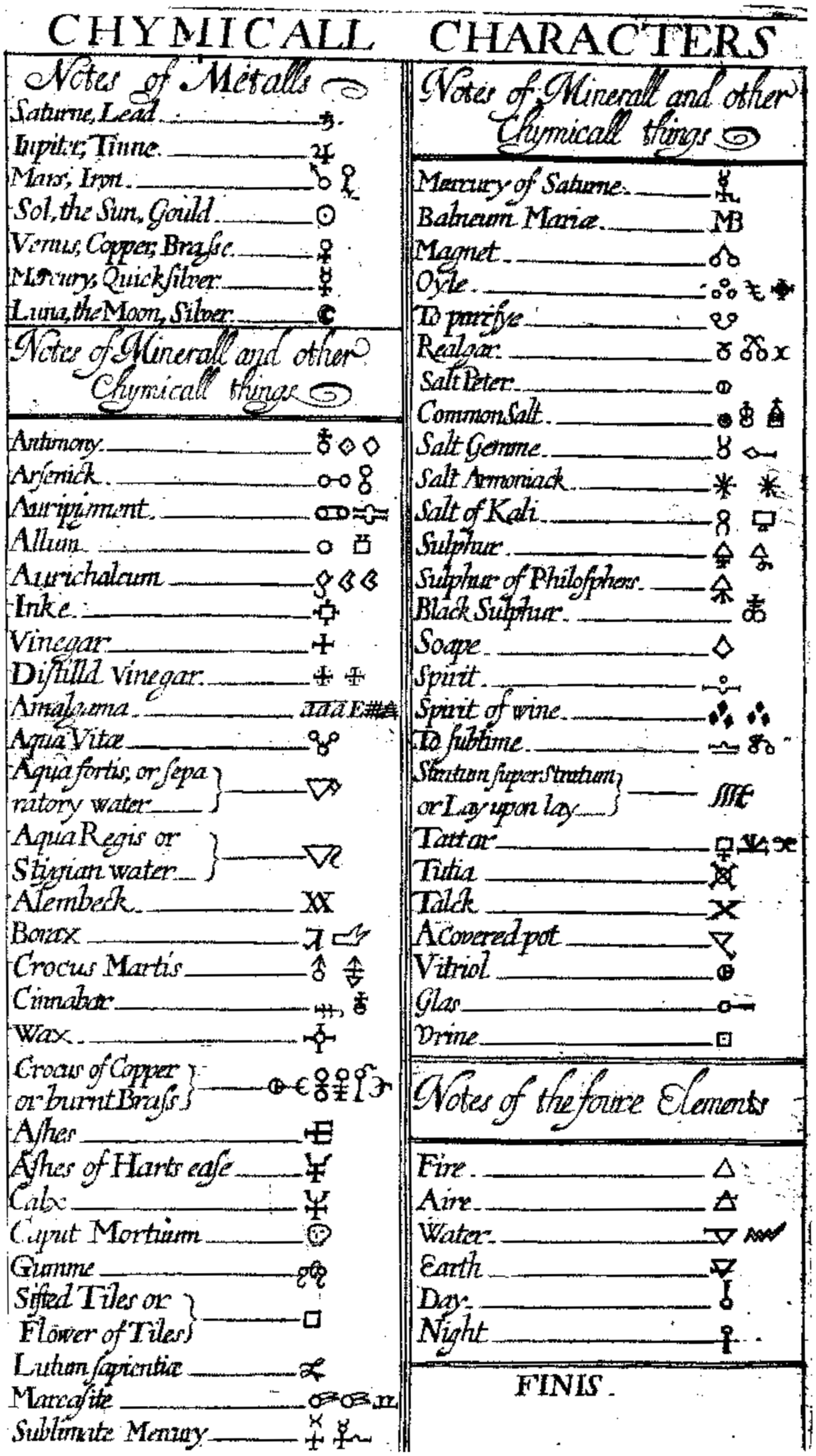
This table of chemical symbols (see Figure 6) is found in the book titled *The Royal Pharmacopoea, Galenical and Chymical, According to the Practice of the Most Eminent and Learned Physitians of France, and Published with their Several Approbations,* the English edition published in 1678. The author, Moses Charas, fled religious persecution in France to join the enlightened intellectual environment in the England of Charles II, who chartered the Royal Society. Its membership included Robert Boyle, Robert Hooke, and Isaac Newton.

The elements listed in the table include the nine ancient elements described previously and a few others readily separable. Gold, of course, being "inert," is commonly found in an uncombined state and its high density (about 9 times denser than sand) allows it to be panned. Actually, we now also know that inert gases such as helium, neon, argon, krypton, and xenon are also found uncombined in nature, but they are colorless and odorless. In any case, we are suddenly over 200 years ahead of ourselves and apologize to the reader for getting carried away by our enthusiasm.

The association of elements with planets and their symbols, evident in Figure 6, appears to have been adopted from the ideas of Arab cultures during the Middle Ages. Association of gold with the sun is too obvious. The others are more subtle. For example, of the planets, mercury appeared to the Ancients to move most rapidly in the sky and was most suited as a messenger. Mercury's wings nicely represent the metal's volatility. In contrast, Saturn was the most distant of planets observed by the Ancients (Uranus, Neptune, and Pluto were discovered in the eighteenth, nineteenth, and twentieth centuries, respectively). The apparent slow movement of this planet through the skies was likened to Saturn, the god of seed or agriculture, who is sometimes depicted with a wooden leg. Lead was dense, slow . . . leaden. A person who is *saturnine* is sluggish or gloomy (not to be confused with a person who is *saturnalian*—riotously merry or orgiastic after the Roman holiday Saturnalia).

But let's return to a modern use of metaphor, based upon the toxic element lead, and visit the book *The Periodic Table,* by Primo Levi,[1] who used 21 elements as metaphors in 21 stories. For example:

> My father and all of us Rodmunds in the paternal line have always plied this trade, which consists in knowing a certain heavy rock, finding it in distant countries, heating it in a certain way that we know, and extracting black lead from it. Near my village there was a large bed; it is said that it



CHYMICALL CHARACTERS

Notes of Metalls

Saturne, Lead	♄
Iupiter, Tinne	♃
Mars, Iron	♂
Sol, the Sun, Gould	☉
Venus, Copper, Braſſe	♀
Mercury, Quickſilver	☿
Luna, the Moon, Silver	☾

Notes of Minerall and other Chymicall things

Antimony	
Arſenick	
Auripigment	
Allum	
Aurichalcum	
Inke	
Vinegar	
Diſtilld Vinegar	
Amalgama	
Aqua Vitæ	
Aqua fortis, or ſeparatory water	
Aqua Regis or Stygian water	
Alembeck	
Borax	
Crocus Martis	
Cinnabar	
Wax	
Crocus of Copper or burnt Braſs	
Aſhes	
Aſhes of Harts eaſe	
Calx	
Caput Mortuum	
Gumme	
Sifted Tiles or Flower of Tiles	□
Lutum ſapientiæ	
Marcaſite	
Sublimate Mercury	

Notes of Minerall and other Chymicall things

Mercury of Saturne	
Balneum Mariæ	MB
Magnet	
Oyle	
To purifye	
Realgar	
Salt Peter	
Common Salt	
Salt Gemme	
Salt Armoniack	
Salt of Kali	
Sulphur	
Sulphur of Philoſphers	
Black Sulphur	
Soape	◇
Spirit	
Spirit of wine	
To ſublime	
Stratum ſuper Stratum, or Lay upon lay	
Tartar	
Tutia	
Talck	
A Covered pot	
Vitriol	
Glaſs	
Vrine	⊡

Notes of the foure Elements

Fire	△
Aire	🜁
Water	▽
Earth	🜃
Day	
Night	

FINIS.

FIGURE 6. ■ Chemical symbols from *The Royal Pharmacopoea* by Moses Charas (London, 1678).

> had been discovered by one of my ancestors whom they called Rodmund Blue Teeth. It is a village of lead-smiths; everyone there knows how to smelt and work it, but only we Rodmunds know how to find the rock and make sure it is the real lead rock, and not one of the many heavy rocks that the gods have strewn over the mountain so as to deceive man. It is the gods who make the veins of metals grow under the ground, but they keep them secret, hidden; he who finds them is almost their equal, and so the gods do not love him and try to bewilder him. They do not love us Rodmunds: but we don't care.
>
> All the men have resumed their former trades, but not I: just as the lead, without us, does not see the light, so we cannot live without lead. Ours is an art that makes us rich, but it also makes us die young. Some say that this happens because the metal enters our blood and slowly impoverishes it; others think instead that it is a revenge of the gods, but in any case it matters little to us Rodmunds that our lives are short, because we are rich, respected and see the world.
>
> So, after six generations in one place, I began traveling again, in search of rock to smelt or to be smelted by other people, teaching them the art in exchange for gold. We Rodmunds are wizards, that's what we are: we change lead into gold.

With the naked eye, ancient people could discern that the planet Mars is red, just as is the calx of iron ("rust"). Associating Mars—the god of war—with iron—the stuff of weapons, as well as with blood—is intuitively reasonable. Late twentieth-century business executives wore red "power ties" to meetings. But in an almost too wonderful confirmation of ancient intuition, the findings of the NASA Viking Mission, which landed two spacecraft on Mars in 1976, indicated a red surface composed of oxides of iron: eyeball chemical analysis by the Ancients at over 30 million miles—not bad!

But let us take irony one or two steps further. As of this writing, it appears that Mars sent its own messenger to Antartica 13,000 years ago in the form of Meteorite ALH84001.[2] Comparison of the carbon isotope content in the carbonate globules of the meteorite with Viking data indicated its Martian origin. Among the fragments of chemical evidence, the finding of iron (II) sulfide coexisting with iron oxides suggested to the investigators a biogenic origin since these two are essentially incompatible under abiotic conditions. The electrifying, although not widely accepted today, conclusion of the scientists[2]:

> Although there are alternative explanations for each of these phenomena taken individually, when they are considered collectively, particularly in view of their spatial association, we conclude that they are evidence for primitive life on early Mars.

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1. P. Levi, *The Periodic Table* (English translation of the Italian text), Schocken Books, New York, 1984 (see pp. 80–81 for the three quotations employed here).
2. D.S. McKay, E.K. Gibson, Jr., K.L. Thomas-Keprta, H. Vali, C.S. Romanek, S.J. Clemett, X.D., F. Chillier, C.R. Maechling, and R.N. Zare, *Science*, 273(5277):924–930, 1996.

PRACTICAL METALLICK CHEMISTRY

Figure 7 depicts the inside view of an assay laboratory of the late sixteenth century. Figures 7 to 17, like Figure 5, are from the 1736 edition of Ercker's *Aula Subterranae . . .* and were printed using plates from the 1574 edition.[1] Figure 8 depicts a machine washing alluvial gold ores. The great density of gold, 19.3 g/cm^3 (the density of water, 1.0 g/cm^3; mercury "only" 13.6 g/cm^3), allows its ready separation from sand and other minerals. Figure 9 depicts the operations in making cupels. Cupellation was a technique for purifying gold or silver in ores. Cupels were cuplike objects made of ground bones in which ground ores were placed. The ores were principally sulfides and heating in air roasted the sulfides and formed oxides of the less noble (more reactive) metals while melting gold or silver. The oxides were absorbed into the cupel while a droplet of gold or silver remained on its surface.

To make cupels, calf or sheep bones are calcined (heated in open air), crushed, and ground to the texture of flour and the "ash" is moistened with strong beer. The ash is then placed in cupel molds (see A and C, Figure 9) and coated with facing ashes, best obtained according to Ercker, from the foreheads of calves' skulls. The molded ash is then pounded and shaped (see H, man pounding cupels), removed from the molds (see B and D and the stack of cupels E), and allowed to dry. In Figure 8, G depicts a man washing ashes and F is a ball of washed ashes.

Figure 10 depicts an assayer's balance including: (A) forged balance beam, (B) shackle, (C) half of shackle, (D) filed assay beam with half of shackle, (E)

FIGURE 7. ■ A sixteenth-century assay laboratory (Ercker, see Figure 5).

FIGURE 8. ■ A sixteenth-century machine washing alluvial gold ores (Ercker, see Figure 5). Gold's great density (19.3 g/cm^3 permits its ready separation from other, lighter minerals.

two little beads—upper end of shackle and pointer, (F) ends, (G) how the beam is suspended, (H) sleeves of shackle, (K) knots by which strings are hung, (L) pans of the balance, and (M) assay head forceps.

Figure 11 depicts the amalgamation of gold concentrates and recovery of mercury by distillation of the amalgam. One of the earliest precepts of chemistry is *like dissolves like*, which explains why oil floats on water while alcohol freely mixes with water. Mercury, being a liquid metal, dissolves other pure metals and forms alloys called amalgams. Relatively mild heating of the amalgam frees the volatile mercury from the metal of interest. However, mercury does not dissolve salts (calxes or oxides, sulfides) of metals. Thus, crushed ore was treated by Ercker with vinegar for 2 or 3 days and then washed and rubbed into mercury by hand and then with a wooden pestle by the amalgamator depicted in Figure 11(F). (*Note:* Elemental mercury is very toxic. It caused nerve damage in workers who made hats in England during the 19th century—this was "Mad Hatters' Disease"—the source of the madness of the tea party in Alice in Wonderland. There has been some concern late in the twentieth century that amalgams used to

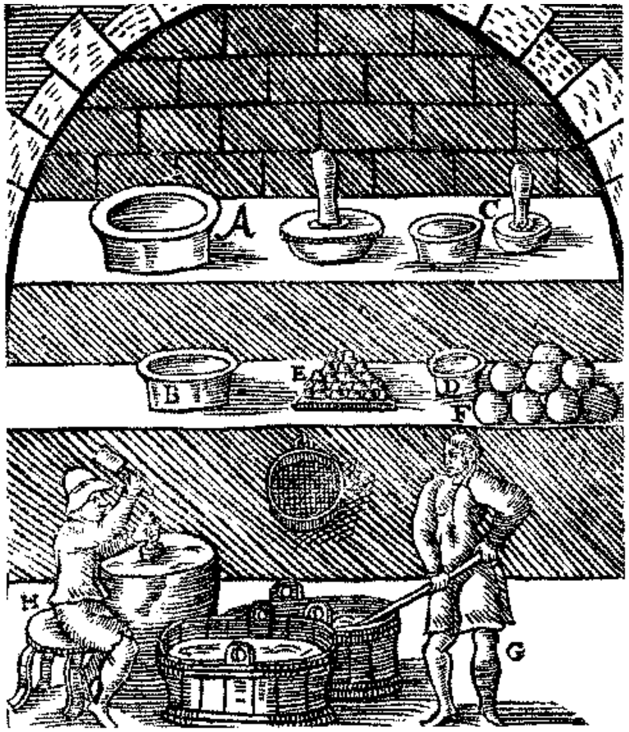


FIGURE 9. ■ Making cupels from calcined, crushed bones ground into a paste with beer and molded. The oxides of baser metals such as iron are absorbed into the cupel while molten gold or silver remain on its surface (Ercker, see Figure 5).

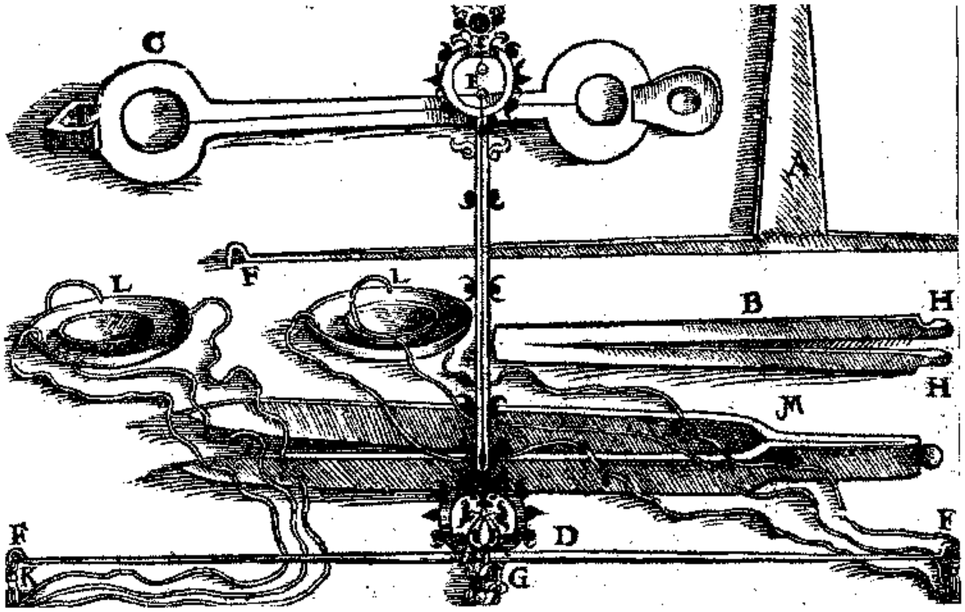


FIGURE 10. ■ A sixteenth-century assayer's balance (see text; Ercker, see Figure 5).

FIGURE 11. ■ Use of mercury to dissolve gold in ore concentrates. The gold amalgam is then heated and mercury distills (Ercker, see Figure 5).

make tooth fillings give off a steady stream of mercury vapor.) The mercury itself was purified by squeezing through a leather bag [see (L) and (G) in Figure 11]. Distillation of mercury from the amalgam employed a large furnace called an athanor (A), which supplied uniform and constant heat, side chambers (B), an earthenware receiver (C) and a still head (D), a blind head through which water can be poured for cooling purposes (E), and an iron pot [lower part (H); upper part (K)] to contain the amalgam to be heated. Also depicted (M) is a man who remelts gold using bellows.

Aqua regia (three parts hydrochloric acid to one part nitric acid) had the valuable property of dissolving gold and allowing its ready recovery (see our later discussion of this subtle chemistry). Figure 12 shows the distillation of *aqua regia* involving the athanor (A) and a chamber (B) for the flask, situated as in (C). (D) is the glass distillation head and (E) the receiver.

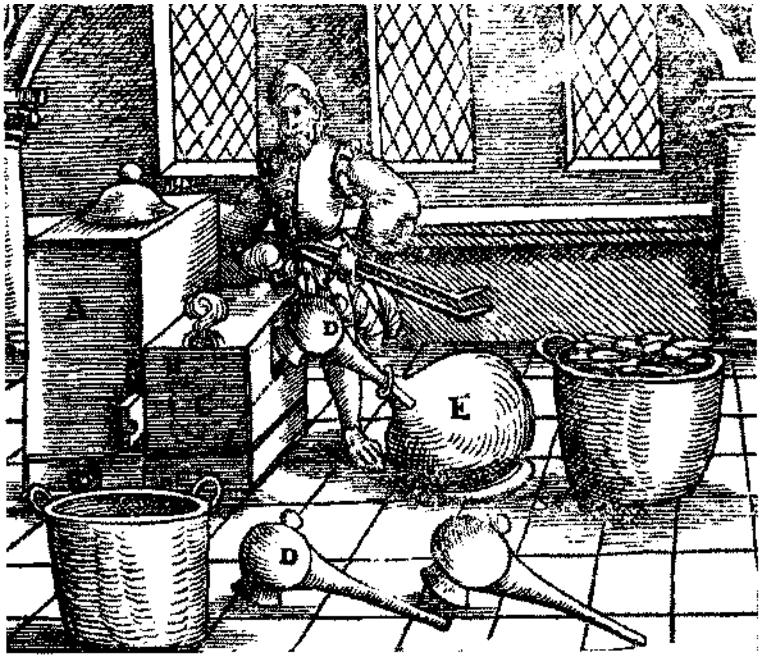


FIGURE 12. ■ Distillation of *aqua regia* (3:1 HCl/HNO_3) (Ercker, see Figure 5). This "kingly water" is capable of dissolving gold. (See essay in Section IX "The Chemistry of Gold is Noble But Not Simple.")

Figure 13 depicts the use of parting acid to separate gold and silver. Parting acid (essentially nitric acid) "dissolves" silver but not gold and is obtained by melting pure saltpetre (potassium nitrate, KNO_3) with vitriol, $FeSO_4$, adding a small amount of water and distilling.

Figure 14 shows a self-stoking furnace for cementation—a process having some similarities to cupellation for purifying gold. The "cement" is made by taking four parts of brick dust, two parts of salt, and one part of white vitriol (zinc sulfate, $ZnSO_4$), grinding the mixed solid, and moistening the powder with urine or sharp wine vinegar. One-finger thickness of the cement is used to cover the bottom of the pot and upon this layer are placed thinly hammered strips of less pure gold, moistened with urine, for further purification. Then follows alternating layers of cement and gold strips finishing with a top layer, one-half-finger thick, of cement. The furnace is applied for 24 hours at a temperature lower than gold's melting point. At the conclusion, the powder is cleaned off and the resulting gold is said to be 23 carat. Pure gold is 24 carat.

Figure 15 depicts the smelting of bismuth in open air with the aid of a very stylized wind. Walnut-sized pieces of ore are placed in pans such that wind-blown fire will smelt the ore and cause liquid bismuth to flow in the pans.

Although saltpetre was used to make nitric acid (for research?) on a small scale, its largest demand was for its use in manufacturing gunpowder. Figure 16 depicts steps in the leaching and concentration, by boiling, of saltpetre. First, the best "earth" for obtaining saltpetre was said by Ercker to come from old sheep pens (which contain the remains of excrement and rotted building matter). Part (A) depicts the "earth" to be leached and (B) shows pipes containing water to

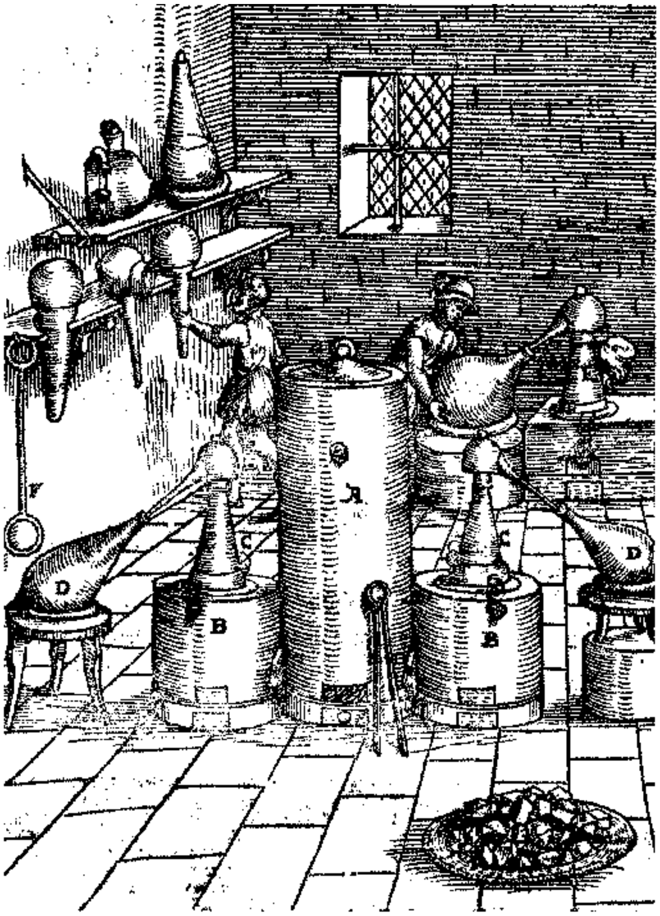


FIGURE 13. ■ The use of "parting acid" (mostly HNO_3) to separate silver from gold. Silver is soluble and gold is not soluble in this acid (Ercker, see Figure 5).

run into the vats. The vats are continuously drained into gutters (C) that run the leachate into a sump (D). Part (E) depicts a little vat from which the leachate runs into a boiler, and (F) to (L) depict parts of the furnace. The boilers distill off considerable water to make a concentrated "liquor."

Figure 17 shows pans (F) and tubs (G) for crystallizing concentrated leachate. One hundred pounds of this concentrate yield about 70 pounds of crystalline saltpetre upon standing.

The development of chemistry rests upon an ancient tripod. One leg of the tripod is formed out of the spiritual, mystical, and conceptual roots of chemistry, which began with the two contraries and four elements, evolved into the *tria prima* (mercury, sulfur, salt) out of which arose Becher's *terra pinguis* or "fatty earth," which, in turn, became Stahl's phlogiston. A second leg is comprised of the practical iatrochemical experience, techniques and apparatus derived from extractions and distillations using animal parts and plants that provided medications. This animal and plant chemistry eventually became our modern organic chemistry and biochemistry. The third leg is the metallurgical chemistry derived from mining and the ancient metallic arts. Aside from techniques learned and appara-

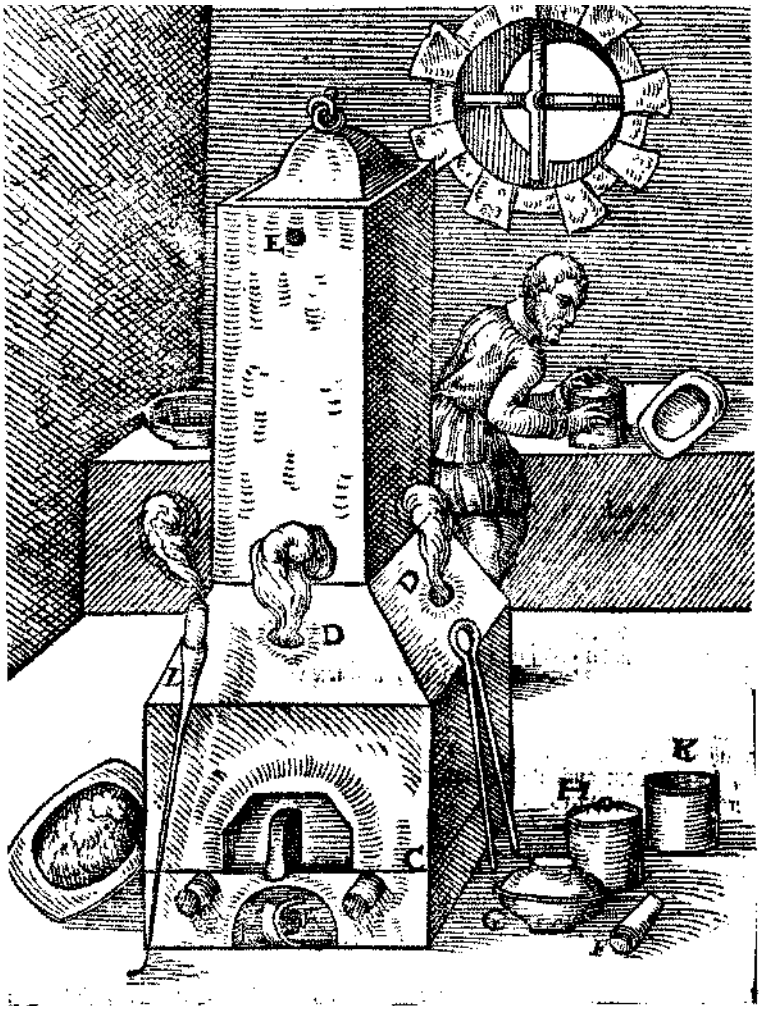


FIGURE 14. ■ A sixteenth-century self-stoking cementation furnace (see text; Ercker, see Figure 5).

tus developed, it was this chemistry—the chemistry of metals and minerals that first truly connected experiment and chemical theory. It ultimately evolved into inorganic chemistry.

In his 1671 book *Metallographia*,[2] John Webster uses biblical quotation to trace metallurgical chemistry back to Moses who, in turn, references Tubal-Cain (*Genesis* 4:22), "the eighth of Mankinde from Adam,"[3] a biblical worker of iron and brass. Here is how Tubal-Cain *might* have discovered metallurgical chemistry:[4]

> While through a Forest Tubal with his yew
> And ready Quiver did a Bore pursue,
> A burning Mountain from his fiery vain,
> An Iron River rolls along the Plain.
> The witty Huntsman musing, thither hies,
> And of the wonder deeply can devise.

FIGURE 15. ■ Smelting of bismuth ore in open wind; freshly formed molten bismuth flows into the pans (Ercker, see Figure 5).

And first perceiving that this scalding mettle
Becoming cold, in any shape would settle,
And grow so hard, that with his sharpened side,
The firmest substance it would soon divide.

Georg Bauer (1494–1555), Latinized as Georgius Agricola (the German *bauer* means "farmer"), studied medicine, probably obtained the M.D. degree in Italy and in 1526 returned to Germany, where he settled in a mining district in Bohemia.[5] Agricola served as a physician to the miners and developed an interest in mining and metallurgical chemistry. Although he wrote a Latin grammar, religious works and a medical work on the plague, his truly lasting works concern metallurgy. Figure 18 shows the title page of Agricola's first book on metallurgy, *Georgii Agricolae Medici Bermannvs, Sive De Re Metallica,* published in Basel in

FIGURE 16. ■ Steps in the leaching and concentration (by boiling) of saltpetre obtained from old sheep dung (Ercker, see Figure 5).

1530 by Froben.[6,7] The "Bermannus" was the first book on the science of mineralogy published in Europe and is of great rarity.[8] The first truly comprehensive book on metallurgical chemistry was the *De La Pirotechnia* of Vannuccio Biringuccio (Venice, 1540), and we will return to it soon.

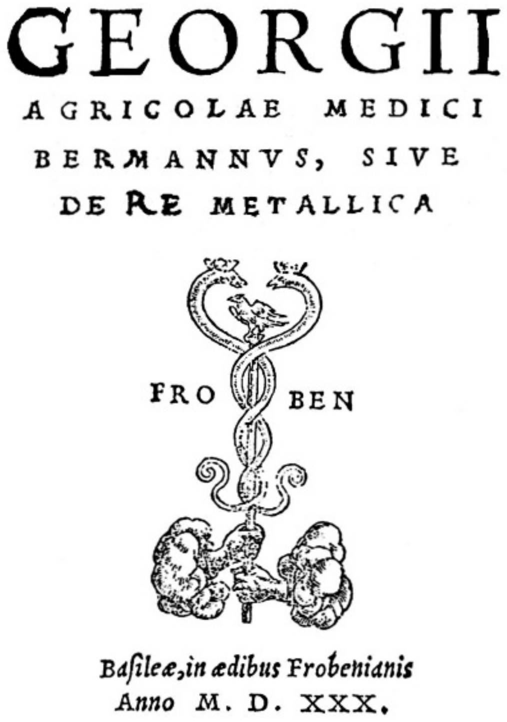
Agricola died a quarter of a century after publication of the 1530 "Bermannus," and during the next year his most famous book, *De Re Metallica Libris XII*,[9] was published in Basel. Although significant sections were adapted from Biringuccio's work as well as other contemporary treatises, Agricola's work summarized a lifetime of experience, observation and learning. His work began with methods of surveying mountains and veins of ore and planning mine shafts. Figure 19, from *De Re Metallica*, illustrates the use of a carefully constructed hemicircle (protractor) and its use for surveying and planning a mine.[9,10] One can only assume that the mining company had progressive managers who encouraged their surveyors to be unencumbered in both their thinking and manner of dress. Figure 20 depicts a horse-driven apparatus for pumping water out of mines. The subterranean chamber was carefully reinforced by timbers to prevent its collapse and the death of the

FIGURE 17. ■ Pans and tubs from crystallizing concentrated leachate for saltpetre (see Figure 16). One hundred pounds of the concentrate yields about 70 pounds of saltpetre (Ercker; see Figure 5).

miners. The hollow plunger had a tightly sealed leather bag at the bottom that pushed air out in the downstroke and drew in drainage water in the upstroke.

Figure 21 shows a laboratory containing stills for the synthesis and purification of "*aqua valens*" or "powerful water."[9,10] Aqua valens was a term used by Agricola for powerful acidic agents, including both *aqua vita* (nitric acid) and *aqua regia* (hydrochloric acid–nitric acid, 3 : 1). (The etymology of "valens" is related to the modern term "valence," which refers to "combining power," for instance, of an atom with one hydrogen atom, two hydrogen atoms, etc.). In Figure 21, a typical distillation of *aqua valens* is represented. It includes an *ampulla* (or cucurbit, *K*) containing a mixture of niter or saltpeter, vitriol, and water along with some alum (aluminum sulfate–potassium sulfate), joining it to an *operculum* (or alembic, *H*). The *operculum* is heated by charcoals (stored in earthenware, *F*) in furnace *A*, red fumes are observed and liquid nitric acid is collected dropwise. Tiny quantities of silver are typically added to the distilled acid in order to precipitate small quantities of chloride that have co-distilled as a result of sea-salt impurities in the starting materials.

The purified nitric acid is used to "part" gold from silver and other base metals because gold is unreactive under these conditions. First, lead is added and



GEORGII
AGRICOLAE MEDICI
BERMANNVS, SIVE
DE RE METALLICA

FRO BEN

Baſileæ,in ædibus Frobenianis
Anno M. D. XXX.

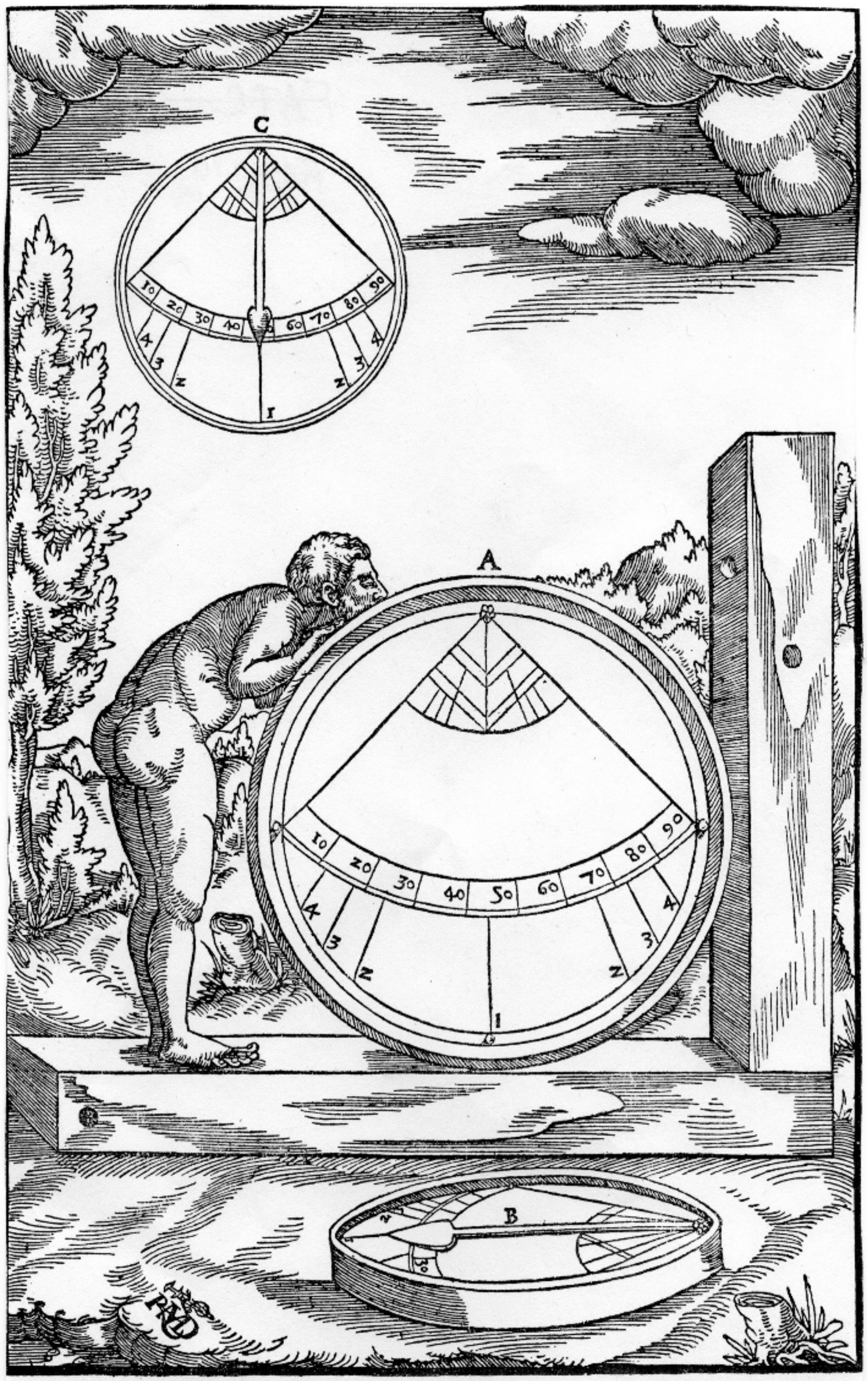
FIGURE 18. ■ Title page from Agricola's first book on metallurgy—the 1530 *Bermannus*. The extensive mining and mineralogy book collection of President Herbert Hoover and Lou Henry Hoover lacked this exceedingly rare book. (From The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF.)

the impure alloy heated in a cupel until the least reactive metals, gold and silver, form a melt while the "baser" metals have oxidized and merged with the bone cupel. The silver-gold alloy is then mixed with the nitric acid—silver dissolves, while gold sinks to the bottom, is filtered, and is then washed.

To this useful scientific knowledge, we must add Agricola's belief in mine "goblins" whose exhalations were deadly to miners.[5] A book concerning subterranean animals published by Agricola in 1549 includes a description of salamanders that survive fire[5] (perhaps taking the salamander allegory, see Figure 49 later in this book, a bit too seriously). Nevertheless, the value of Agricola's famous book was well stated by Webster—never a shy critic, in 1671, over a century after *De Re Metallica* was published:[11]

> As for the beating, grinding, sifting, and washing of Ores in general, from their earthy filthiness and superfluitities, Georgius Agricola hath written very largely and learnedly, more than any other Author that I know of. And I could with that some person that hath ability and leisure, would translate it into English; for it might be very serviceable to our common Miners, that in that particular have little to direct them, but what they learn from one another.

Webster's wish was finally answered some 241 years later by two people of very considerable ability and very little leisure: Herbert Hoover, the future president



A—Standing plummet level. B—Tongue. C—Level and tongue.

FIGURE 19. ■ Surveying the coordinates of a mine (on a sweltering summer day?) from the 1912 Hoover translation of Agricola's most famous book, the 1556 *De Re Metallica Libris XII*.

A—UPRIGHT AXLE. B—TOOTHED WHEEL. C—TEETH. D—HORIZONTAL AXLE. E—DRUM WHICH IS MADE OF RUNDLES. F—SECOND DRUM. G—DRAWING-CHAIN. H—THE BALLS.

FIGURE 20. ■ A horse-driven apparatus for pumping water out of mines (from the 1912 Hoover translation of Agricola's 1556 *De Re Metallica*). Agricola believed in mine goblins whose emanations (carbon monoxide?) were deadly to miners.

A—Furnace. B—Its round hole. C—Air-holes. D—Mouth of the furnace. E—Draught opening under it. F—Earthenware crucible. G—Ampulla. H—Operculum. I—Its spout. K—Other ampulla. L—Basket in which this is usually placed lest it should be broken.

FIGURE 21. ■ Distillation of *aqua valens* ("powerful water"), a general term used by Agricola to describe powerful acids such as *aqua fortis* (nitric acid) and *aqua regia* (hydrochloric acid/nitric acid, 3 : 1), depicted in the 1912 Hoover translation of Agricola's 1556 *De Re Metallica.*

of the United States of America, and his wife Lou Henry Hoover, the first female geology graduate of Stanford University (see the next essay).

Vannucio Biringuccio (1480–1539) is much less well known than Agricola.[5] However, his *Pirotechnia* (Venice, 1540)[12] was the first comprehensive book on mining and metallurgy and was sumptuously illustrated.[5] Amazingly, its first English translation appeared over four centuries later in 1942![13] Biringuccio was very much involved in the political affairs of his day, had military knowledge and skill and was Director of the Pope's (!) Arsenal[5] (much as Lavoisier over two centuries later would direct the Arsenal of Louis XVI). He did not believe in transmutation and was one of the earliest to note the increase in weight of lead upon its calcination:[14]

> The calcination of lead in a reverberatory furnace seems to me to be such a fine and important thing that I cannot pass by it in silence. For it is found in effect that the body of the metal increases in weight to 8 or perhaps 10 per

> hundred more than it was before it was calcined. This is a remarkable thing when we consider that the nature of fire is to consume everything with a diminution of substance, and for this reason the quantity of weight ought to decrease, yet actually it is found to increase.

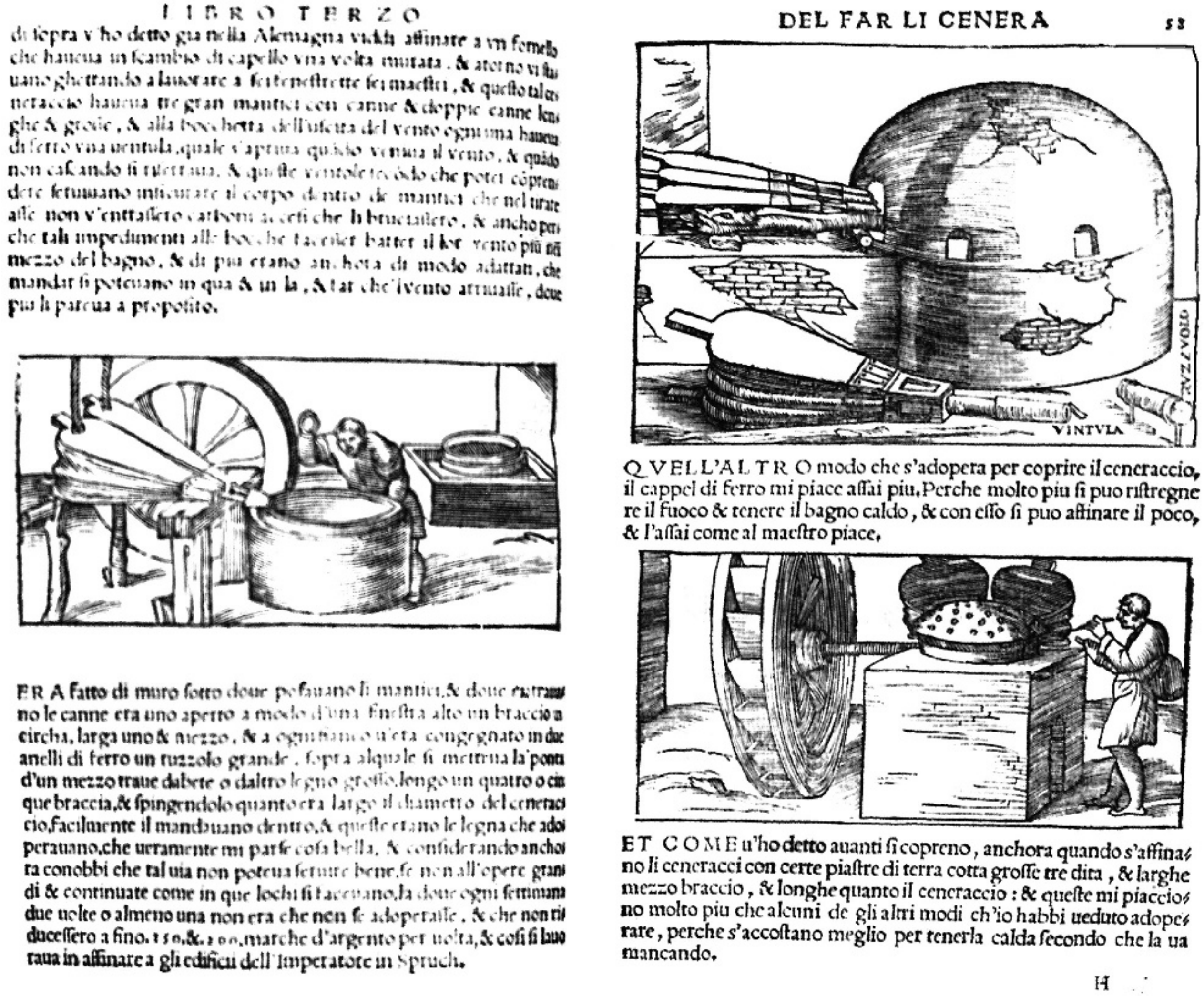
We know now that oxidation of lead to form lead oxide (PbO) should involve a weight increase relative to the metal of 7.7%.

Figures 22 and 23 are from the 1540 *Pirotechnia*. They depict five different types of large cupeling furnaces. Typically, we think of cupels as small molded cups made, for example, from calcined crushed bone ground into a paste with beer, molded, dried, and baked.[14] Crude silver ore may be heated to high temperature in these cupels. More reactive metals oxidize and their calxes are physically absorbed into the cupels leaving molten silver to be cooled and form the purified solid. The huge cupels in Figures 22 and 23 were made from wood ashes, crushed brick, limestone, and egg white and were employed to purify large quantities of silver.[15] The figure at the left (verso page) of Figure 22 shows a worker forming the hearth of a large cupeling furnace.[15] The upper and lower figures to the right (recto page) of Figure 22 are large cupeling furnaces with a brick dome and an iron hood, respectively. The upper figure on the verso page in Figure 23 is a cupeling hearth covered with clay plates, and the lower figure depicts a cover of wooden logs over a cupeling hearth.[15]

Agricola's *De Re Metallica* and Biringuccio's *Pirotechnia* are both recognized as "Heralds of Science—two hundred epochal books and pamphlets in the Dibner Library, Smithsonian Institution."[16] One additional mining and metallurgy book has also been included on this rarified list—*Beschreibung: Allerfürnemisten Mineralischen Ertzt Unnd Berckwercks Arten* ("Treatise Describing the Foremost Kinds of Metallic Ores and Minerals," 1574, Prague) by Lazarus Ercker described earlier in this section (Figures 7–17). Figure 24 is from the title page of the second (1580) edition of this beautiful folio book.[1,17] It depicts a full array of operations in a sixteenth-century mineral assayer's laboratory. The sumptuous book was published in eight Frankfort editions beginning in 1574 with the final one appearing in 1736.[1] The wonderful wood blocks used to print the illustrations in 1574 were preserved and used through 162 years in all eight editions.[1] A Dutch edition was published in 1745.

It is interesting that the first two of the three great mining, assaying, and metallurgy books of the sixteenth century were finally translated into English roughly four centuries after their original publication: Biringuccio's *Pirotechnia* (Venice, 1540; Chicago, 1942); Agricola's De Re Metallica (Basel, 1556; London, 1912). However, Ercker's *Beschreibung* (Frankfurt, 1574) was translated by Sir John Pettus[18] about one century (London, 1683) after the Frankfurt original. Anneliese Grünhaldt Sisco and Cyril Stanley Smith conjecture that the reason for the earlier English translation of Ercker's book in the seventeenth century might have been that it was the most recent, and thus current, of the three great texts. Pettus (1613–1690) played a significant military role in England's Civil War and, at one point, was held captive by Oliver Cromwell for 14 months. Following the restoration, Pettus served as Restoration Deputy to the Vice Admiral and was seriously wounded in the leg during a naval battle with the Dutch.[18]

An interesting aspect of Pettus' translation of Ercker's book (*Fleta Minor, or, the Laws of Art and Nature, In Knowing, Judging, Assaying, Fining, Refining and In-*



LIBRO TERZO

di ſopra v'ho detto gia nella Alemagna viddi affinare a vn fornello che haueua in ſcambio di capello vna volta murata. & atorno vi ſtauano ghettando a lauorare a ſei feneſtrette ſei maeſtri, & queſto tal ceneraccio haueua tre gran mantici con canne & doppie canne longhe & groſſe, & alla bocchetta dell'uſcita del vento ognuna haueua di ferro vna uentola, quale s'apriua quando veniua il vento, & quãdo non caſcando ſi riſerraua. & queſte ventole tenẽdo che potei cõprendere ſeruiuano inſicurare il corpo dentro de mantici che nel tirare aſſe non v'entraſſero carboni acceſi che li bruciaſſero, & ancho perche tali impedimenti alle bocche faceſſer batter il lor vento piu nel mezzo del bagno. & di piu erano anchora di modo adattati, che mandar ſi poteuano in qua & in la, & far che'l vento arriuaſſe, doue piu li pareua a propoſito.

ERA fatto di muro ſotto doue poſauano li mantici, & doue entrauano le canne era uno aperto a modo d'una fineſtra alto un braccio a circha, larga uno & mezzo, & a ogni fianco u'era congegnato in due anelli di ferro un ruzzolo grande, ſopra alquale ſi metteua la ponta d'un mezzo traue dabete o daltro legno groſſo, longo un quatro o cinque braccia, & ſpingendolo quanto era largo il diametro del ceneraccio, facilmente il mandauano dentro, & queſte erano le legna che adoperauano, che ueramente mi parſe coſa bella, & conſiderando anchora conobbi che tal uia non poteua ſeruire bene, ſe non all'opere grandi & continuate come in que lochi ſi faceuano, la doue ogni ſettimana due uolte o almeno una non era che non ſe adoperaſſe, & che non riduceſſero a fino. 150. & 200. marche d'argento per uolta, & coſi ſi lauoraua in affinare a gli edificii dell'Imperatore in Spruch.

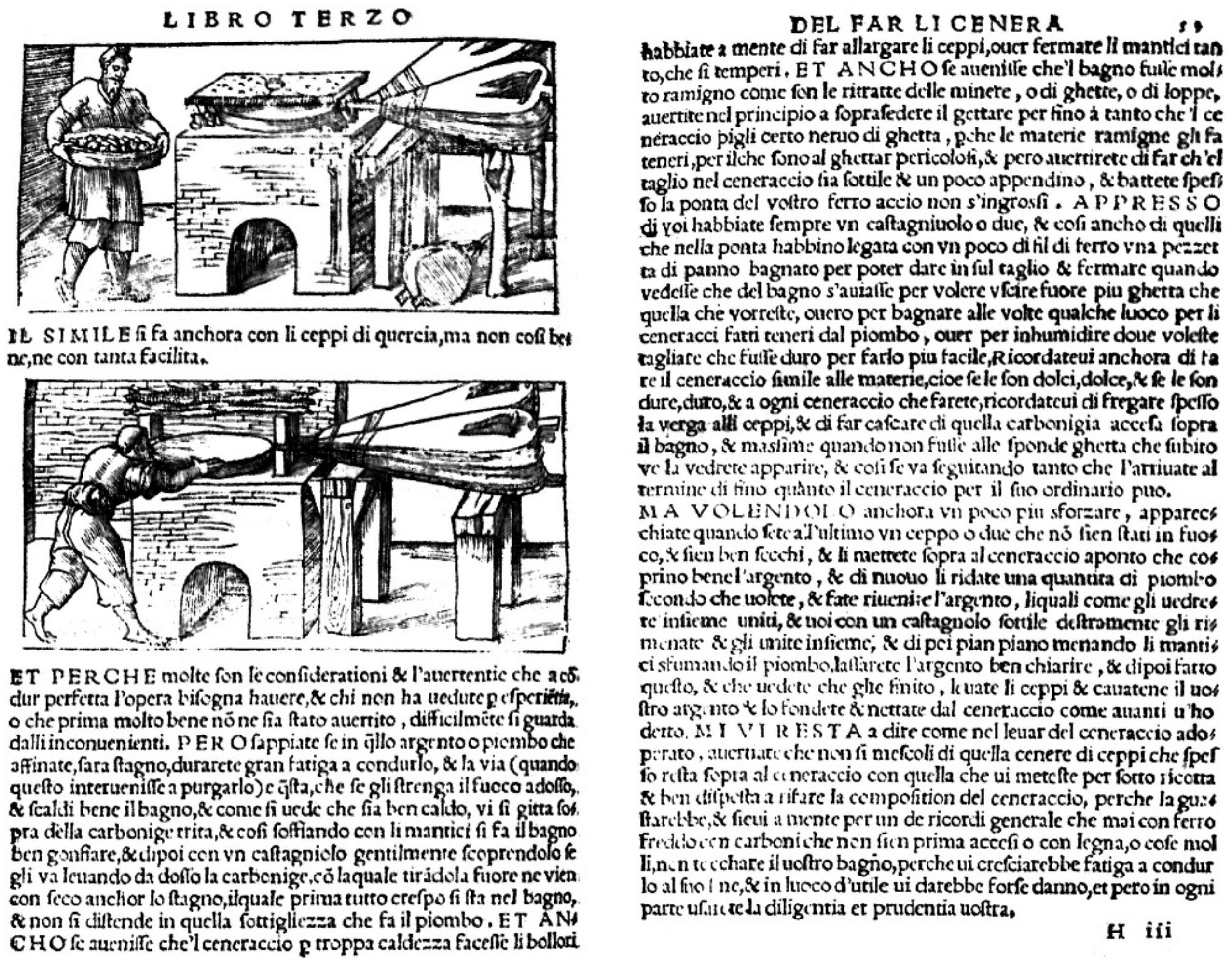
DEL FAR LI CENERA 53

QVELL'ALTRO modo che s'adopera per coprire il ceneraccio, il cappel di ferro mi piace aſſai piu. Perche molto piu ſi puo riſtregnere il fuoco & tenere il bagno caldo, & con eſſo ſi puo affinare il poco, & l'aſſai come al maeſtro piace.

ET COME u'ho detto auanti ſi copreno, anchora quando s'affinano li ceneracci con certe piaſtre di terra cotta groſſe tre dita, & larghe mezzo braccio, & longhe quanto il ceneraccio: & queſte mi piacciono molto piu che alcuni de gli altri modi ch'io habbi ueduto adoperare, perche s'accoſtano meglio per tenerla calda ſecondo che la ua mancando.

H

FIGURE 22. ■ Large cupeling furnaces depicted in Vannucio Biringuccio's 1540 *Pirotechnia.* Cupels are cups made typically from crushed bone ground into a paste with beer, then molded, dried, and baked. Calxes of base metals (e.g., iron oxides) are absorbed into the cupel while molten gold is not and is thus readily separable. (From The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF.)



LIBRO TERZO

IL SIMILE ſi fa anchora con li ceppi di quercia, ma non coſi bene, ne con tanta facilita.

ET PERCHE molte ſon le conſiderationi & l'auertentie che a condur perfetta l'opera biſogna hauere, & chi non ha uedute ꝑ eſperientia, o che prima molto bene nõ ne ſia ſtato auertito, difficilmẽte ſi guarda dalli inconuenienti. PERO ſappiate ſe in q̃llo argento o piombo che affinate, ſara ſtagno, durarete gran fatiga a condurlo, & la via (quando queſto interueniſſe a purgarlo) e q̃ſta, che ſe gli ſtrenga il fuoco adoſſo, & ſcaldi bene il bagno, & come ſi uede che ſia ben caldo, vi ſi gitta ſopra della carbonige trita, & coſi ſoffiando con li mantici ſi fa il bagno ben gonfiare, & dipoi con vn caſtagniolo gentilmente ſcoprendolo ſe gli va leuando da doſſo la carbonige, cõ laquale tirãdola fuore ne vien con ſeco anchor lo ſtagno, ilquale prima tutto creſpo ſi ſta nel bagno, & non ſi diſtende in quella ſottigliezza che fa il piombo. ET ANCHO ſe aueniſſe che'l ceneraccio ꝑ troppa caldezza faceſſe li bollori

DEL FAR LI CENERA 59

habbiate a mente di far allargare li ceppi, ouer fermare li mantici tanto, che ſi temperi. ET ANCHO ſe aueniſſe che'l bagno fuſſe molto ramigno come ſon le ritratte delle minere, o di ghette, o di loppe, auertite nel principio a ſopraſedere il gettare per fino à tanto che 'l ceneraccio pigli certo neruo di ghetta, ꝑche le materie ramigne gli fa teneri, per ilche ſono al ghettar pericoloſi, & pero auertirete di far ch'el taglio nel ceneraccio ſia ſottile & un poco appendino, & battete ſpeſſo la ponta del voſtro ferro accio non s'ingroſſi. APPRESSO di voi habbiate ſempre vn caſtagniuolo o due, & coſi ancho di quelli che nella ponta habbino legata con vn poco di fil di ferro vna pezzetta di panno bagnato per poter dare in ſul taglio & fermare quando vedeſſe che del bagno s'auiaſſe per volere vſcire fuore piu ghetta che quella che vorreſte, ouero per bagnare alle volte qualche luoco per li ceneracci fatti teneri dal piombo, ouer per inhumidire doue voleſte tagliare che fuſſe duro per farlo piu facile, Ricordateui anchora di fare il ceneraccio ſimile alle materie, cioe ſe le ſon dolci, dolce, & ſe le ſon dure, duro, & a ogni ceneraccio che farete, ricordateui di fregare ſpeſſo la verga alli ceppi, & di far caſcare di quella carbonigia acceſa ſopra il bagno, & maſſime quando non fuſſe alle ſponde ghetta che ſubito ve la vedrete apparire, & coſi ſe va ſeguitando tanto che l'arriuate al termine di fino quanto il ceneraccio per il ſuo ordinario puo.

MA VOLENDOLO anchora vn poco piu sforzare, apparecchiate quando ſete a l'ultimo vn ceppo o due che nõ ſien ſtati in fuoco, & ſien ben ſecchi, & li mettete ſopra al ceneraccio aponto che coprino bene l'argento, & di nuouo li ridate una quantita di piombo ſecondo che uolete, & fate riuenire l'argento, liquali come gli uedrete inſieme uniti, & uoi con un caſtagnolo ſottile deſtramente gli rimenate & gli unite inſieme, & di poi pian piano menando li mantici ſfumando il piombo, laſſarete l'argento ben chiarire, & dipoi fatto queſto, & che uedete che gl'e finito, leuate li ceppi & cauatene il uoſtro argento & lo fondete & nettate dal ceneraccio come auanti u'ho detto. MI VI RESTA a dire come nel leuar del ceneraccio adoperato, auertiate che non ſi meſcoli di quella cenere di ceppi che ſpeſſo reſta ſopra al ceneraccio con quella che ui meteſte per ſotto ricotta & ben diſpeſta a rifare la compoſition del ceneraccio, perche la guaſtarebbe, & ſieui a mente per un de ricordi generale che mai con ferro freddo o con carboni che non ſien prima acceſi o con legna, o coſe molli, non toccharete il uoſtro bagno, perche ui creſciarebbe fatiga a condurlo al ſuo fine, & in luoco d'utile ui darebbe forſe danno, et pero in ogni parte uſarete la diligentia et prudentia uoſtra.

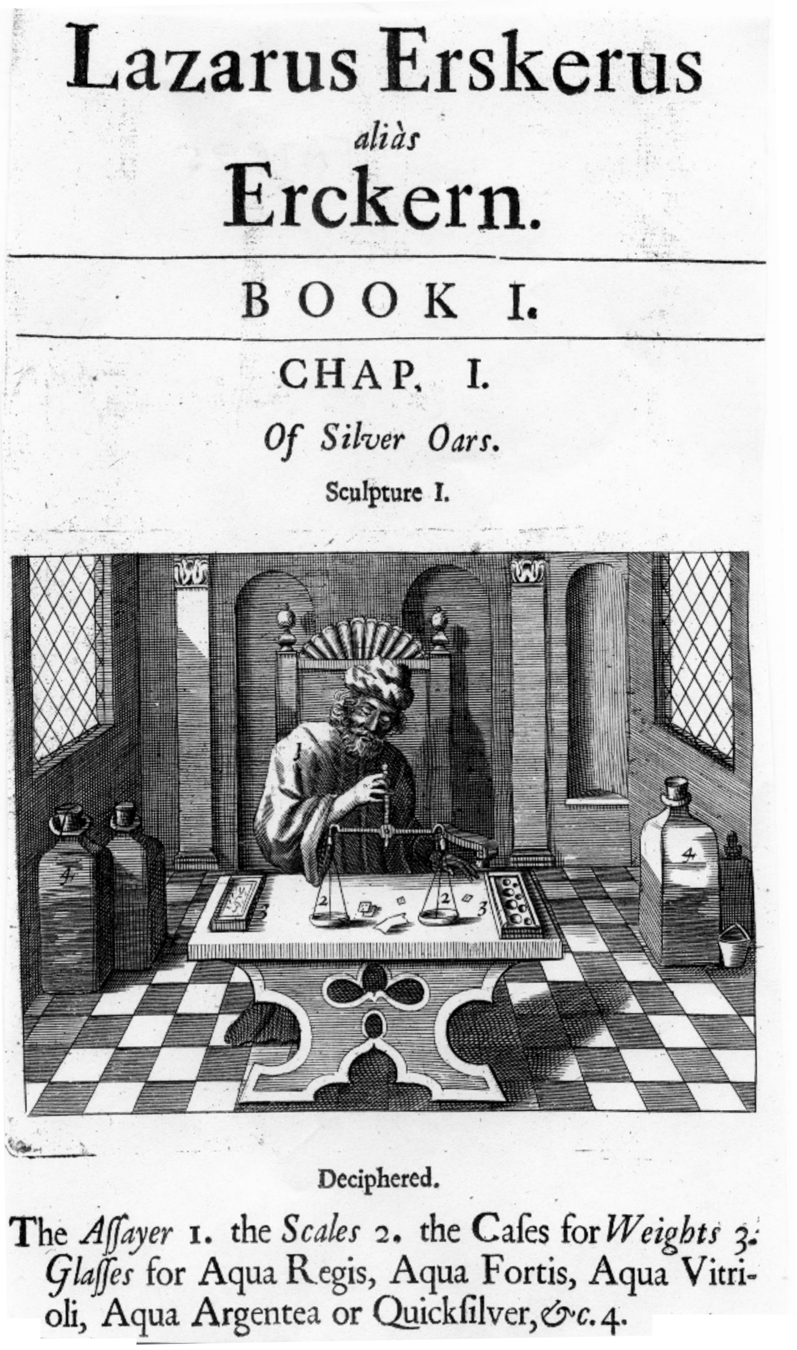
H iii

FIGURE 23. ■ Large cupeling hearths from Biringuccio's 1540 *Pirotechnia* (from The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF).

FIGURE 24. ■ A sixteenth-century mineral assayer's laboratory from the second (1580) edition of Lazarus Ercker's treatise on mining and metallurgy. The woodblock used to print the first edition (1574), and this (second) edition was preserved and employed for over 160 years through the final 1736 edition. (From The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF.)

larging the Bodies of confin'd Metals), is the replacement of Ercker's sixteenth-century woodcuts with late-seventeenth-century costumed English figures engraved in copper plates. Figure 49 depicts a contemporary English assayer. Figures 25–29 include partial explanations with the plates. Figure 26 describes the making and molding of cupels made from crushed bone paste. Figure 27 is a scene in a gold-assaying laboratory. The cone-shaped vessel on the right is a parting flask, for assaying gold, seated on its stand. The wooden piece hanging to the right of the assayer in the rear of this figure has a slit through which to view the furnace while protecting the eyes. The person in the foreground is testing the density of "auriferous" silver in water. The *aqua fort* referred to in Figure 28 is nitric acid. Figure 29 depicts the smelting of bismuth in open air. It is fun to compare Figures 26, 28 and 29 with their sixteenth-century German counterparts (Figures 9, 12, and 15).

The curious title of Pettus' book, *Fleta Minor,* derives from the final years of his life that were spent in the "Fleta" or Fleet Prison wherein he wrote this work. Pettus informs his readers that "it seems a strange disposition of Providence that a man who had done so much for his King and Country should be suffered through the accusations of an unscrupulous woman, and that woman his own wife, to spend the closing years of an active and useful life a Prisoner in the Fleet."[18]



Lazarus Erskerus
aliàs
Erckern.

BOOK I.

CHAP. I.
Of Silver Oars.
Sculpture I.

Deciphered.

The *Aſſayer* 1. the *Scales* 2. the Caſes for *Weights* 3. *Glaſſes* for Aqua Regis, Aqua Fortis, Aqua Vitrioli, Aqua Argentea or Quickſilver, &c. 4.

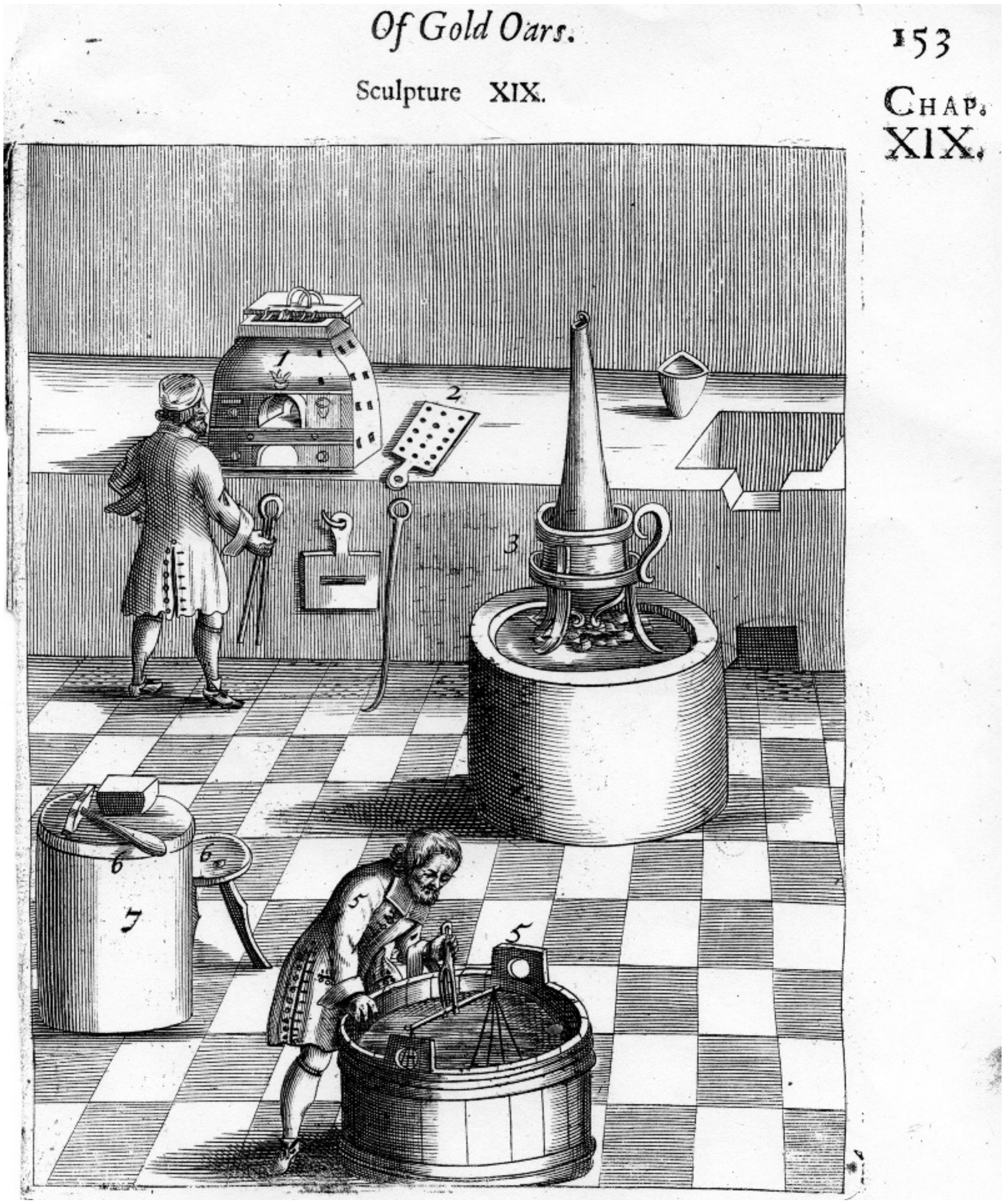
FIGURE 25. ■ Depiction of an assayer in John Pettus' 1683 translation and extension of Ercker's treatise on metallurgy. Pettus' book title begins "*Fleta Minor*," referring to the Fleet Prison, in which he was an inmate while writing this book. Pettus was imprisoned "through the accusations of an un-scrupulous woman" who was, incidentally, his wife.

Now, how the *Copel-Caſe* and the Copel is to be ordered and performed the following *Sculpture* will ſhew.

Sculpture V.

Deciphered.

FIGURE 26. ■ Manufacture of cupels (using a paste made from crushed bone and beer) from Pettus' 1683 *Fleta Minor*. Compare this figure with the corresponding one (Figure 9) in the 1736 edition (i.e., the original 1574 edition), and you will note that costumes have been updated by a century while the apparatus remains unchanged.



Of Gold Oars.

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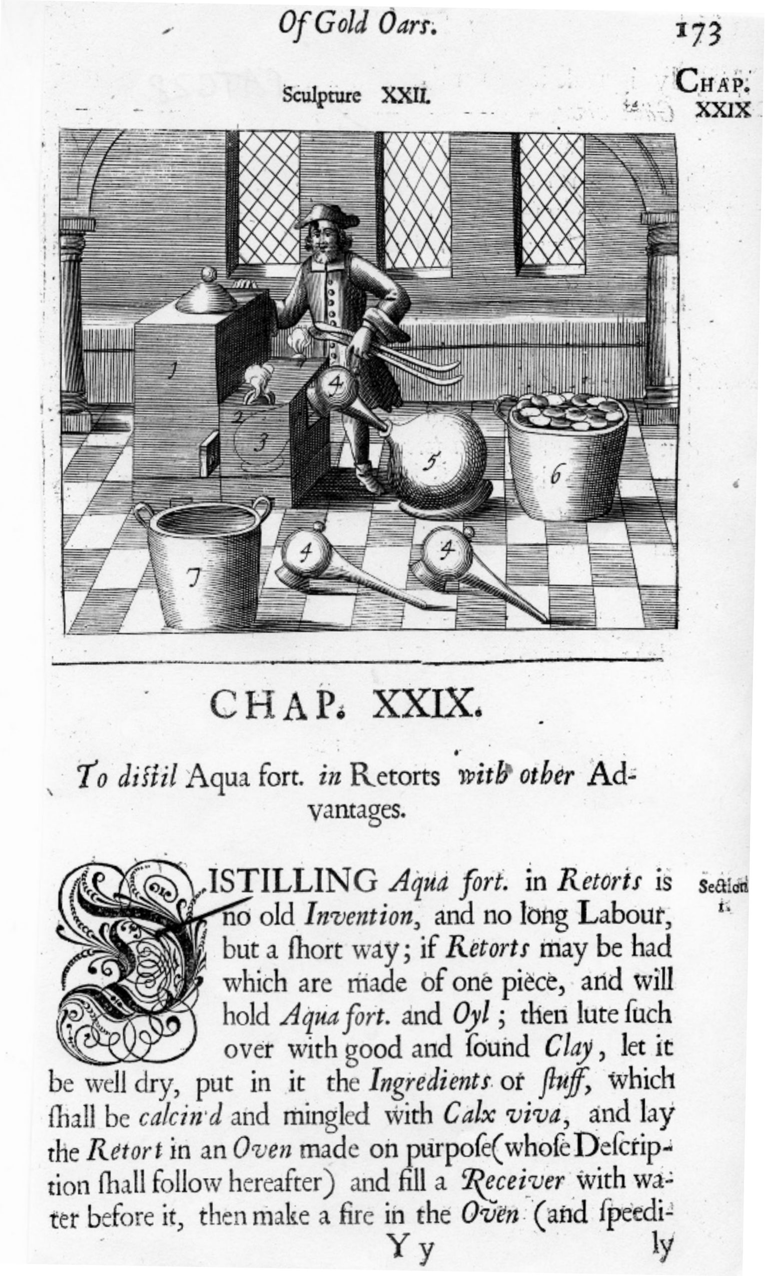
Sculpture XIX.

CHAP. XIX.

FIGURE 27. ■ Assaying gold ore in Pettus' 1683 *Fleta Minor*.



Of Gold Oars. 173

Chap. XXIX

Sculpture XXII.

CHAP. XXIX.

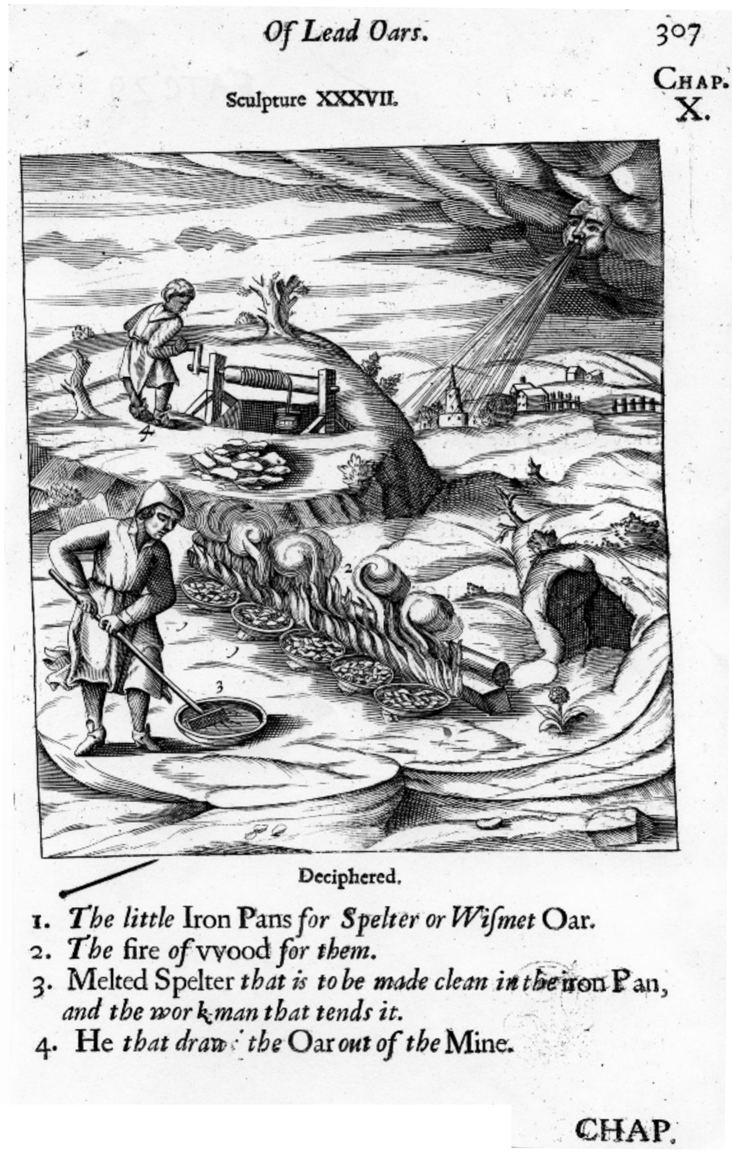
To diſtil Aqua fort. *in* Retorts *with other* Advantages.

DISTILLING *Aqua fort.* in *Retorts* is no old *Invention*, and no long Labour, but a ſhort way; if *Retorts* may be had which are made of one piece, and will hold *Aqua fort.* and *Oyl*; then lute ſuch over with good and ſound *Clay*, let it be well dry, put in it the *Ingredients* or *ſtuff*, which ſhall be *calcin'd* and mingled with *Calx viva*, and lay the *Retort* in an *Oven* made on purpoſe (whoſe Deſcription ſhall follow hereafter) and fill a *Receiver* with water before it, then make a fire in the *Oven* (and ſpeedi-

Section 1.

Yy ly

FIGURE 28. ■ Distillation of aqua fortis (nitric acid) in Pettus' 1683 *Fleta Minor*. Compare this figure with the corresponding one (Figure 12) in the 1736 edition (i.e., the original 1574 edition), and you will note that the costumes have been updated by a century while the apparatus remains unchanged.



Of Lead Oars. 307

CHAP. X.

Sculpture XXXVII.

Deciphered.

1. *The little* Iron Pans *for Spelter or Wiſmet* Oar.
2. *The* fire *of* vvood *for them.*
3. Melted Spelter *that is to be made clean in the* iron Pan, *and the wor k man that tends it.*
4. He *that draws the* Oar *out of the* Mine.

CHAP.

FIGURE 29. ■ Smelting of bismuth ore in the open wind from Pettus' 1683 *Fleta Minor.* Compare this figure with the corresponding one (Figure 15) in the 1736 edition (i.e., the original 1574 edition), and you will note that costumes have been updated by a century while the apparatus remains unchanged.

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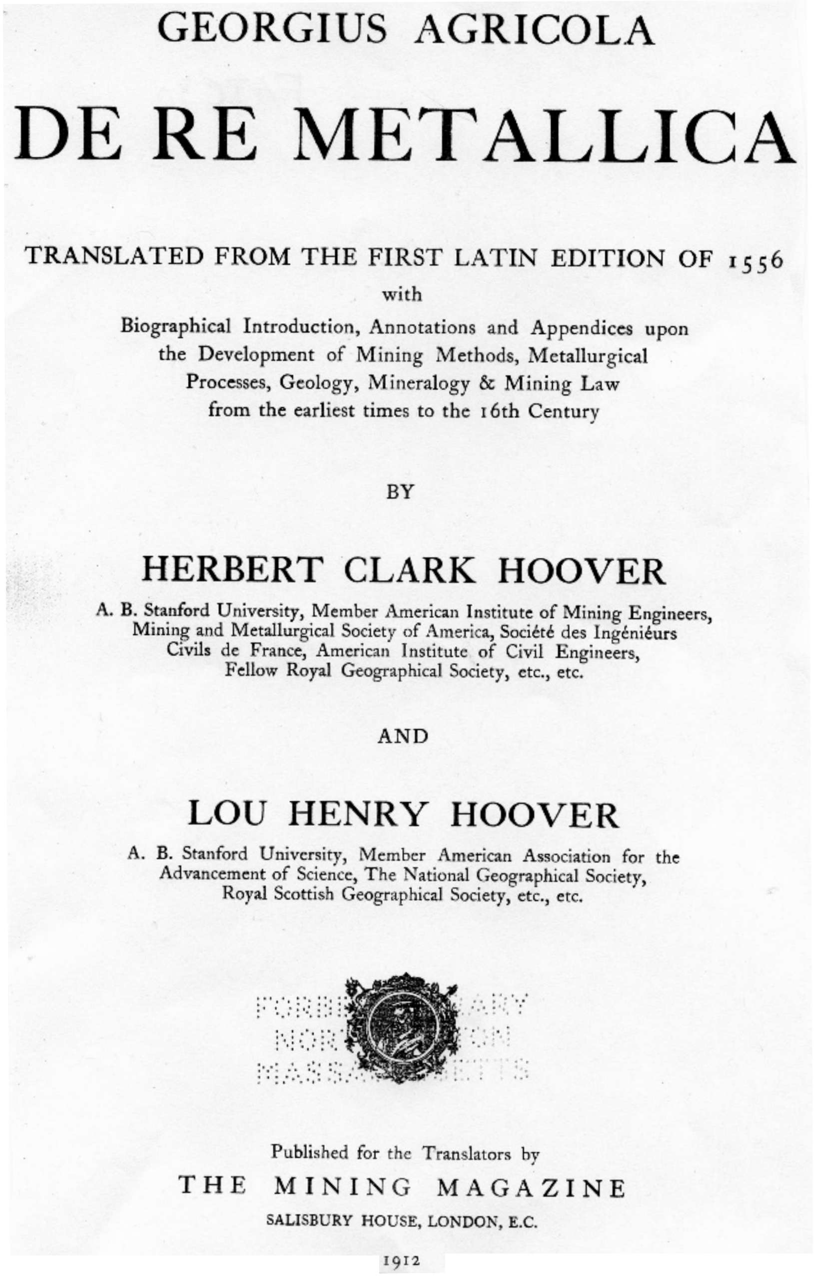
1. A.G. Sisco and C.S. Smith (transl.), *Lazarus Ercker's Treatise on Ores and Assaying* (translated by Anneliese Grünhaldt Sisco and Cyril Stanley Smith from the German edition of 1580), The University of Chicago Press, Chicago, 1951. I employed this source for interpretations.
2. J. Webster, *Micrographia: Or, An History of Metals,* Walter Kettilby, London, 1671.
3. J. Read, *Humour and Humanism in Chemistry,* G. Bell and Sons Ltd., London, 1947, pp. 3–4.
4. Webster, op. cit., p. 3.
5. J.R. Partington, *A History of Chemistry,* MacMillan and Co. Ltd., London, 1961, Vol. 2, pp. 32–66.
6. G. Agricola, *Georgii Agricolae Medici Bermannus, sive De Re Metallica,* Frobenianus, Basel, 1530. I thank The Roy G. Neville Historical Chemical Library (California) for supplying the image of the title page for this book.

7. Johann Froben (Johannes Frobenius, ca. 1460–1527) was a famous Basel printer-publisher whose techniques revolutionized printing. Among his gifted illustrators were Hans Holbein, and after 1513 he was the sole publisher of the great Dutch humanist-philosopher Desidarius Erasmus (*The New Encyclopedia Britannica,* Encyclopedia Britannica, Inc., Chicago, 1986, Vol. 5, p. 16.).
8. I thank The Roy G. Neville Historical Chemical Library (California) for supplying this image, and I am grateful to Dr. Neville for helpful discussions.
9. G. Agricola, *De Re Metallica Libri XII, Quibis Officia, Instrumenta, Machinae, Ac Omnia Denique Ad Metallicam Spectantia,* Basel, 1556. I am grateful to Ms. Elizabeth Swan, Chemical Heritage Foundation, for providing these images.
10. H.C. Hoover and L.H. Hoover (transl.), *Georgius Agricola De Re Metallica* (translated from the first Latin edition of 1556), *The Mining Magazine,* London, 1912 (reprinted by Dover Publications, Inc., New York, 1950), see pp. 439–447.
11. Webster, op. cit., p. 155.
12. V. Biringuccio, *De La Pirotechnia. Libri X.,* Venice, 1540. I am grateful to Ms. Elizabeth Swan, Chemical Heritage Foundation, for supplying images from this book.
13. C.S. Smith and M.T. Gnudi, *The Pirotechnia of Vannoccio Biringuccio Translated from the Italian with an Introduction and Notes by Cyril Stanley Smith and Martha Teach Gnudi,* The American Institute of Mining and Metallurgical Engineers, New York, 1942 (see also the 1959 reprint published by Basic Books, New York).
14. Smith, op. cit., p. 58.
15. Smith, op. cit., pp. 161–169.
16. *Heralds of Science,* revised edition, Burndy Library and Smithsonian Institution, Norwalk and Washington, DC, 1980. It has been duly noted that, of the *Great Books of the Western World,* published by Encyclopedia Britannica in 1952, only one work (of a collection of 130 authors and 517 works) is a treatise on chemistry (Lavoisier's *Traité élémentaire de Chimie,* Paris, 1789, first English translation, 1790) [R. Wedin, Chemistry (published by the American Chemical Society), Spring 2001, pp. 17–20]. Wedin surveyed a small, selected list of chemists and librarians to obtain his list of "The Great Books of Chemistry." The six books on "The Gold Shelf" included Lavoisier's Traité, Boyle's *The Sceptical Chymist,* Jane Marcet's *Conversations on Chemistry* (a useful and influential textbook that drew the young Michael Faraday into chemistry), Dalton's *A New System of Chemical Philosophy,* Mendeleev's *Osnovy Khimii,* and Pauling's *The Nature of the Chemical Bond.* "The Silver Shelf" comprised six additional books including Agricola's *De Re Metallica.* "The Bronze Shelf" included 12 books. Of the total of 24 books, thirteen were American publications, and two of these were published by the American Chemical Society itself. Hmmm.
17. L. Ercker, *Beschreibung Allefürnemisten Mineralischen Ertzt vnnd Bergwercks arten . . . ,* Johannem Schmidt in verlegung Sigmundt Feyrabends, Frankfurt, 1580. I am grateful to The Roy G. Neville Historical Chemical Library (California) for supplying the image of the title page.
18. Sisco and Smith, op. cit., pp. 340–342.

A PROMISING PRESIDENT

The first English translation of Agricola's 1556 *De Re Metallica*[1] (Figure 30) was published in 1912 by Herbert C. Hoover (1874–1964),[2] the future president of the United States, and his wife, Lou Henry Hoover. It is hard to imagine a more promising future president. Born in rural Iowa to Quaker parents of extremely modest means, Herbert Hoover was orphaned by the age of nine. Although shy, he developed a very early sense of independence, rejected the choice of Quaker colleges suggested to him by his relatives, and chose to attend a brand new college, Stanford University. Hoover majored in geology and met Lou Henry, the



GEORGIUS AGRICOLA

DE RE METALLICA

TRANSLATED FROM THE FIRST LATIN EDITION OF 1556
with
Biographical Introduction, Annotations and Appendices upon
the Development of Mining Methods, Metallurgical
Processes, Geology, Mineralogy & Mining Law
from the earliest times to the 16th Century

BY

HERBERT CLARK HOOVER
A. B. Stanford University, Member American Institute of Mining Engineers,
Mining and Metallurgical Society of America, Société des Ingéniéurs
Civils de France, American Institute of Civil Engineers,
Fellow Royal Geographical Society, etc., etc.

AND

LOU HENRY HOOVER
A. B. Stanford University, Member American Association for the
Advancement of Science, The National Geographical Society,
Royal Scottish Geographical Society, etc., etc.

Published for the Translators by
THE MINING MAGAZINE
SALISBURY HOUSE, LONDON, E.C.
1912

FIGURE 30. ■ Title page from the first English translation of Agricola's 1556 *De Re Metallica*, written and tested for scientific accuracy by engineer Herbert Hoover, the future President of the United States, and his wife Lou Henry Hoover, the first female geology graduate of Stanford University.

only female geology major at Stanford. They married in 1899 and remained happily united until her death in 1944. She was a smart, independent, and forceful woman, raised as a tomboy and adept at riding horses, and later became a powerful champion of women's suffrage.[2] Not long after graduating from Stanford in 1895, Herbert Hoover began a career in mining engineering and management that soon would make him wealthy and possibly the world's most famous engineer. He spent most of his time overseas during the following decades and was in China during the Boxer Rebellion (1900), where he directed relief for foreigners.[2]

The Hoovers amassed a huge and famous mining book collection and, during the course of writing their translation, performed occasional experiments to test Agricola's veracity.[3] The challenge of the Hoovers' translation is not "merely" mastery of Latin but also a profound understanding of the engineering and chemistry, which allowed them to incorporate hundreds of now-defunct terms and concepts and make sense out of them for the modern reader. Not many years after this intellectual triumph, with the outbreak of World War I Herbert Hoover was appointed head of the Allied relief operation. After the American entry into the war in 1917, he was appointed national food administrator. Hoover's efforts at increasing food production, conserving foodstocks and relieving famine in Europe were so successful that the term "hooverize"[4] entered the vocabulary as an expression symbolizing the acts of being productive, economical, and generous with foodstocks. Even more generally, it became a term for efficiency, effectiveness, and compassion.

How ironic, then, that Herbert Clark Hoover, thirty-first president of the United States (1928–1932), is now principally remembered for his failure to ease the hardships of the Great Depression. Very strict ethical values inculcated in early childhood and reinforced by his own very early independence (and subsequent success) made widespread federal aid, particularly to the urban unemployed, anathema to him.[2] He was widely regarded as distant from the suffering populace.[2] And so, sadly enough, "hooverville,"[4] a shanty town populated by the unemployed poor, is a word both more recent and more widely remembered than "hooverize."

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1. H.C. Hoover and L.H. Hoover, *Georgius Agricola De Re Metallic* (translated from the first Latin edition of 1556), *The Mining Magazine*, London, 1912.
2. J.H. Wilson, *Herbert Hoover—Forgotten Progressive*, Little, Brown and Co., Boston, 1975.
3. Wilson, op. cit., pp. 22–23.
4. *Oxford English Dictionary*, second ed., Vol. VII, Clarendon Press, Oxford, 1989, p. 374.

THESE ARE A FEW OF OUR NASTIEST THINGS

It is generally agreed that gunpowder (black powder) was invented in China over a thousand years ago.[1] It is a mixture consisting of about 75% saltpetre (potassium nitrate) with the remaining 25% containing comparable quantities of charcoal and sulfur. Saltpetre was readily obtained from old dung heaps; charcoal readily made by heating vegetables or wood under oxygen-poor conditions; sulfur was found in crystalline deposits and could also be obtained by heating many metal ores. William Brock has speculated, rather ironically, I think, that the Chinese accidentally discovered gunpowder through seeking an elixir of life by a combination of the "Yin-rich saltpetre and Yang-rich sulphur."[1] There is further irony in that gunpowder held secret keys to understanding the origins of fire and the very respiration that supports life. However, these would remain hidden for almost a millennium. Early hints would be provided by Boyle, Hooke, and Mayow in the mid-seventeenth century and the riddle solved by Lavoisier over a century later.

Gunpowder was introduced quite early into Western warfare. Figure 31 is from the first Stainer edition of the ancient book on the technology of warfare authored by Flavius Vegetius Renatus.[2] This excessively rare edition, published in 1529, contains the first printed text on making gunpowder, along with directions for purifying its components.[3] Figure 32 is from a 1598 work on artillery and fireworks by Alessandro Capo Bianco,[4] Captain of Bombadiers at Crema in the

FIGURE 31. ■ Figure from the first Stainer edition (Augsburg, 1529) of the ancient work by Flavius Vegetius Renatus on the technology of warfare (from The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF).

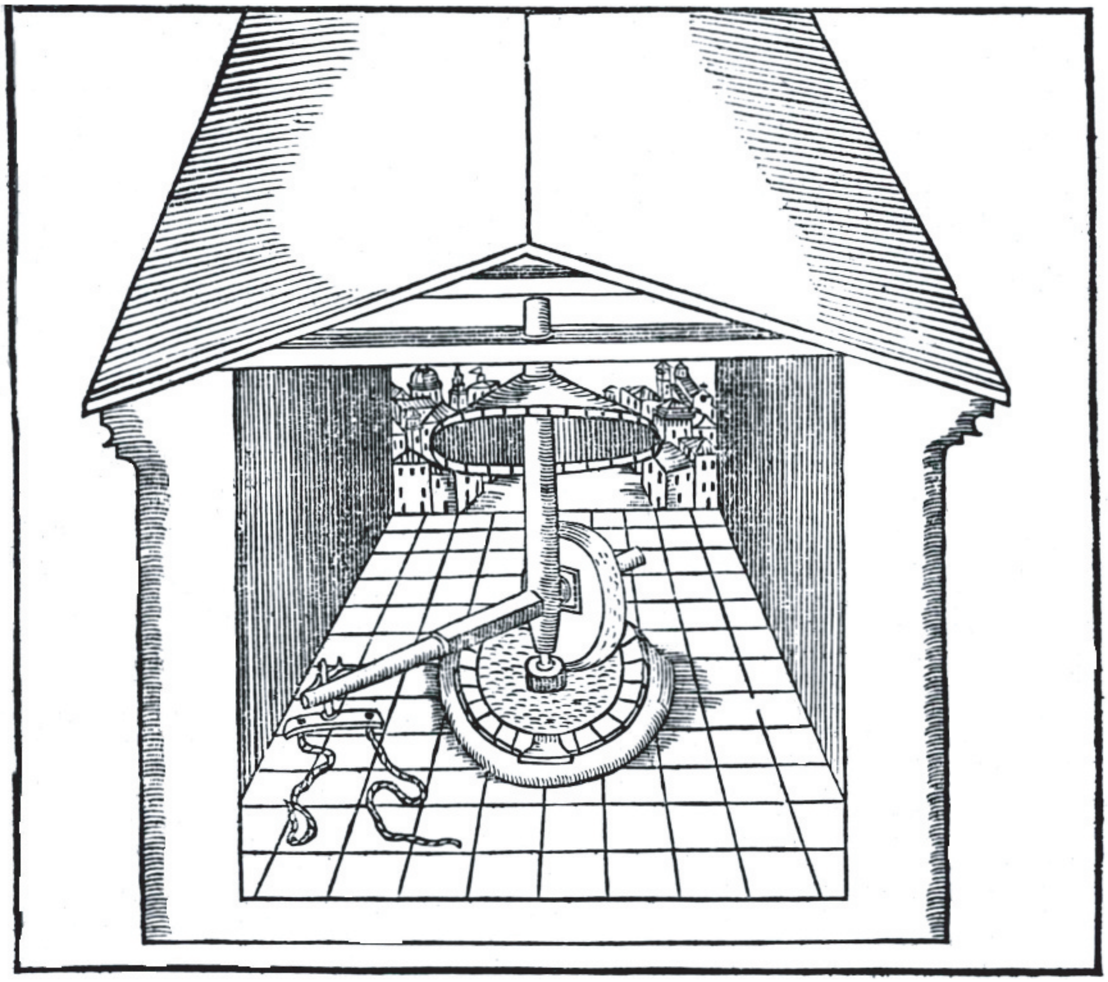

FIGURE 32. ■ Mill for grinding the components of gunpowder (ca. 75% saltpetre; the remainder roughly equal parts of charcoal and sulfur) depicted in Bianco's 1598 work on artillery and fireworks (from The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF).

Veneto. The figure depicts a sixteenth-century mill for grinding components of gunpowder.[3] In Book Ten of his *Pirotechnia* (1540),[4] Biringuccio provides detailed directions for making gunpowder. Saltpetre is derived from the "manurous" soils of barns and the floors and walls of caves (rich in bat guano), which contain calcium nitrate as a decomposition product. If the "manurous" soil, once dried, is tasted and found to be "sufficiently biting," it is suitable for use.[5] The soil is added to boiling water, and wood ashes (rich in "pearl ash" or potassium carbonate) are stirred in. The hot solution is then filtered and allowed to cool; the resulting crystalline potassium nitrate is filtered and recrystallized once more with water and a bit of nitric acid.[5] Charcoal is made preferably from willow twigs by heating over fire in a large sealed earthen pot. The components of gunpowder must be moistened before being ground together, to avoid ignition, and Biringuccio recommends slow addition of finely ground sulfur to a paste of moistened charcoal and saltpetre.[5]

Biringuccio begins his chapter on gunpowder thus:[5]

> A great and incomparable speculation is whether the discovery of compounding the powder used for guns came to its first inventor from the demons or by chance.

At many points in Book Ten, Biringuccio laments the irony that learned and decent men discover and invent explosives that maim and kill. He then dutifully describes their fabrication in full detail. For example, Book Ten, Chapter Eight is titled "The Method of Preparing Fire Pots and of Making Balls of Incendiary Composition to Be Thrown by Hand." Biringuccio begins this chapter (in the 1559 edition):[6]

> There have always been in this world men of such keen intelligence that with their discourse they have been capable of infinite and various inventions that are as beneficial as they are simultaneously harmful to the human body.

He then describes pots made of dried clay filled with course gunpowder, pitch, and sulfur, and sealed with congealed pig fat mixed with powder (see Figure 33).[7] Prior to use, a small hole is bored into the fatty seal and either a fuse or black powder placed inside. The fuse or powder is lit, the pot tossed or launched with a sling and this penetrating, sticky mass will adhere to and burn its target.

Other early explosives and incendiary weapons included "Greek Fire" dating from the Hellenistic period. Chemical historian John Hudson describes "Greek Fire" as a liquid that caught fire on contact with water and speculates that calcium phosphide (from heating bones, lime and urine together), added to crude petroleum might have constituted the active ingredients.[8] Leonardo Da Vinci (1452–1519) described "Greek Fire" as consisting of charcoal, sulfur, pitch, saltpeter, spirit of wine, frankincense, and camphor boiled together and applied over Ethiopian wool.[9]

FIGURE 33. ■ Nasty munitions made from clay pots filled with coarse gunpowder, pitch, and sulfur, and sealed with congealed pig fat mixed with powder depicted in Biringuccio's *Pirotechnia*. These are manufactured to be lighted and launched with malice using a sling. (From The Roy G. Neville Historical Chemical Library, a collection in the Othmer Library, CHF.)

Fulminating gold (*aurum fulminans*) was first described at the beginning of the seventeenth century.[10] Gold was dissolved in an *aqua regia* derived from ammonium chloride and nitric acid. Addition of potassium carbonate led to a precipitate that, when dry, exploded readily with only the mildest application of heat. Johann Rudolph Glauber first described fulminating powder (*pulvis fulminans*) in 1648.[10] It is a mixture of potassium nitrate, potassium carbonate, and sulfur that violently explodes upon mild heating. Tenney Davis has described various similar mixtures discovered over the course of two centuries.[10] In the late seventeenth century Johann Kunckel made mercury fulminate by dissolving mercury in *aqua fortis* (nitric acid), adding spirit of wine and gently warming the mixture in horse dung.[11] The next day, the concoction exploded violently.

The nineteenth century would witness the development of nitrostarch, nitrocotton, nitroglycerin, trinitrotoluene (TNT), and pentaerythritol tetranitrate (PETN) and end with the discovery of RDX (cyclotrimethylenetrinitramine).[12] Contemporary studies of synthetic azides and picrates would also add to the armamentarium of war technology. From a modern perspective these developments appear to have grimly foreshadowed World War I. In 1867, Alfred Nobel (1833–1896), a Swedish chemist and industrialist, immobilized nitroglycerin onto diatomaceous earth, making it much safer to use, and thus made the first of many successful formulations of dynamite.[12] Just as hope often accompanies tragedy, Nobel willed most of his vast fortune to establish a series of Nobel Prizes—one of which is a prize to further the cause of world peace.

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1. W.H. Brock, *The Norton History of Chemistry,* W.W. Norton & Co., New York, 1993, p. 6. Brock notes that in Taoism, "Yang" is the male, hot principle, "Yin" is the female, cool principle. In Western alchemical beliefs, sulfur is the male principle (Sol) and mercury the female principle (Luna).
2. F. Vegetius Renatus, *Vier Bũcher der Ritterschaft . . . Mit einem zũsatz von Bũchsen geschoss, Pulver, Fewrwerck, Auff ain newes gemeeret unnd gebessert, Gedruckt durch Heinrich Stainer,* Augsburg, 1529.The author is grateful to The Roy G. Neville Historical Chemical Library for supplying a copy of the woodcut in Figure 31.
3. The Roy G. Neville Historical Chemical Library; catalogue in preparation. I am grateful to Dr. Neville for helpful discussions.
4. Alessandro Capo Bianco, *Corona e Palma Militare di Arteglieria. Nella quale si tratta dell' Inventione di essa, e dell' operare nella fattioni da Terra, e Mare, fuochi artificiati da Giucco, e Guerra; & d'un Nuovo Instrumento per misurare di stanze. Con una giunta della fortificatione Moderna, e delli errori scoperti nelle fortezze antiche, tutto a proposito per detto essercitio dell' Artiglieria, con dissegni apparenti, & assai intendenti. Nova composta, e data in luce. Dallo strenuo Capitano Alessandro Capo Bianco . . .* Appresso Gio. Antonio Rampazetto, Venice, 1598.
5. C.S. Smith and M.T. Gnudi, *The Pirotechnia of Vannoccio Biringuccio* (English transl.), The American Institute of Mining and Metallurgical Engineers, New York, 1942, pp. 409–416. This is the first English translation of Biringuccio's *De La Pirotechnia* published in Venice in 1540.
6. Smith and Gnudi, op. cit., pp. 434–435.
7. The author thanks The Roy G. Neville Historical Chemical Library (California) for supplying this image from the 1540 edition of *De La Pirotechnia.*
8. J. Hudson, *The History of Chemistry,* The MacMillan Press Ltd, Hampshire and London, 1992, p. 22.
9. J.R. Partington, *A History of Chemistry,* MacMillan and Co. Ltd., London, 1961, Vol. 2, p. 6.
10. T.L. Davis, in *Chymia,* T.L. Davis (ed.), Vol. 2, University of Pennsylvania Press, Philadelphia, 1949, pp. 99–110.

11. Partington, op. cit., p. 377.
12. D.M. Considine (ed.), *Van Nostrand's Scientific Encyclopedia,* seventh edition, Van Nostrand Reinhold, New York, 1989, pp. 1104–1105.

"THE SUN RAINS GOLD; THE MOON RAINS SILVER"

In 1532, Spanish Commander Francisco Pizarro and a force of 168 soldiers compelled the surrender of the Nation of Incas that ruled a population of 12,000,000 people stretching from present-day Quito, Ecuador, to the south of Santiago, Chile. The conventional explanation for this has rested on the technical superiority of the Spanish and other European peoples, although it is admitted that the Europeans imported diseases such as smallpox, for which the aboriginal peoples had no resistance, which decimated their populations. In his compelling 1994 book, *Guns, Germs and Steel,*[1] the biologist and geographer Jared Diamond provides insights into the advantages enjoyed by Europeans: native horses rather than llamas too small to ride into combat, steel swords against bronze technology, and guns versus arrows.

The Incas, one of a number of ancient Andean native cultures, established their capitol in Cuzco in what is now southern Peru in the twelfth century. In the early fifteenth century, they began the series of conquests that would gain them the empire that Pizarro encountered and ruthlessly destroyed. It appears, however, that the technological advantages of the Europeans over the Incas may well be overstated.[2] Rifles of the sixteenth century were barely effective: they required about 2 to 3 minutes per shot and were notoriously inaccurate. The original name for these weapons, *donderbus* (German for "thunder box"), was soon changed to the more realistic "blunderbuss." In contrast, arrows could be launched at 10 per minute and were accurate at 200 yards.[2]

The rivers in the Andes were rich sources of gold and the mines rich sources of silver. It is fascinating that, much like ancient Asian and Arabic cultures, Andean cultures equated gold with the Sun and maleness, and silver with the Moon and femaleness. "The Sun rains gold; the Moon rains silver" is an ancient Andean invocation. Aboriginal cultures in the New World, such as those in the Andes, relied upon oral rather than written historical records and there are no manuscripts describing formulas and procedures. Only detailed investigations of the artifacts themselves provide clues about the level of technology. Recent evidence indicates that Andean metallurgy dates back at least 3,000 years. In 1998, researchers at Yale University discovered samples of gold foil that had been both hammered into thin sheets and heat treated (annealed) so as to gild metal objects, including those made of copper.[3,4] However, despite an abundant supply of iron in the mountains, Andean cultures did not fabricate steel. Heather Lechtman, at MIT, observes that Europeans optimized "hardness, strength, toughness, and sharpness" in metals.[5–7] In contrast, Andean cultures, including the Incas, valued "plasticity, malleability, and toughness." Rather than employing metals as weapons and machine parts, they fashioned objects that were employed to communicate social standing, wealth, and religious authority.[2,5–7] Most of the Andean metallurgical operations focused on gold, silver, and copper, although bronze and lead slingshot weapons were known. Early Andean metallurgists plated very thin (0.5–2 micron) and uniform layers of gold on copper metal and alloys despite their lack of aqua regia as well as electroplating technology[7] (see page 575).

Professor Lechtman demonstrated some of the sophistication of Andean metallurgy and engineering in her analysis of architectural cramps (metal bars bent at the ends to hold together stone blocks) from the Middle Horizon (ca. AD 600–1000).[8] The I-shaped cramps held together large stone blocks that formed the sides of canals for conducting collected rain water, serving the ancient city of Tiwanaku, presently a village in Bolivia, near the southern shore of Lake Titicaca. The design of the canal was quite sophisticated. Although the canal sloped 12°, the spaces for the cramps in adjoining blocks were cut horizontally so as to tightly lock the blocks into place. The canal is water-tight despite the fact that the blocks are not cemented together. In some cases, spaces have been cut into adjoining blocks that act as cramp molds to receive freshly molten bronze. Modern chemical analyses (neutron activation and ion-coupled emission analyses) have determined that these cramps are ternary bronze alloys of copper, arsenic,

FIGURE 34. ■ Thomas de Bry's 1596 engraving depicting Incan gold workers (from the first German edition of 1597).[8]

and nickel. The alloy was developed to provide a residual tensile stress when solidified, which held the blocks tightly together.

Although the Incas did not add much to the existing Andean metallurgical technology,[5,6] they were skilled at the craft. Figure 34 is from the 1597 first German edition of the *Americae pars sexta* . . . ,[9] first published in Latin in 1596 by the renowned engraver Thomas de Bry (1528-1598). It depicts sixteenth century Incan gold workers heat-treating metals and hammering them into sheets. In contrast to the metal sculptures of Europeans, which were obtained using molds, the Incans fashioned art objects such as the statue in the lower right of Figure 34 from thin plates. Dr. Lechtman has furnished a beautiful example in which a miniature head only 1.3 cm high and 0.012–0.02 cm thick is made from 19 individual gold plates that have been hammered and then skillfully soldered or welded together.[5]

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5. H. Lechtman, "Traditions and Styles in Central Andean Metalworking," in *The Beginning of the Use of Metals and Alloys, Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys,* Zhengchou, China, 21–26 October, 1986, R. Madden, ed., The MIT Press, Cambridge, MA, 1988, pp. 344–378. (I am grateful to Professor Lechtman for correspondence on this topic and for supplying reprints of her work.)
6. H. Lechtman, "The Andean World," in *Andean Art at Dumbarton Oaks*, E.H. Boone, ed., 1996, pp. 11–43.
7. H. Lechtman, "Pre-Columbian Surface Metallurgy," *Scientific American,* Vol. 250, No. 6 (June 1984), pp. 56–63. The Author thanks Professor Roald Hoffmann for awareness of this work.
8. H. Lechtman, "Architectural Cramps at Tiwanaku: Copper–Arsenic–Nickel Bronze," in *Metallurgica AntiquaI in Honour of Hans-Gert Bachmann and Robert Maddin,* T. Rehren, A. Hauptmann, and J.D. Muhly (eds.), Deutches Bergbau-Museum Bochum, 1998, pp. 77–92.
9. T. de Bry, *Americae pars sexta. Sive, Historiae ab Hieronymo Be[n]zono scriptae, section tertia . . . In hac . . . reperies qua ratione Hisponi . . . Peruäni regni provincias occuparint, capto rege Atabaliba . . . Additus est . . . de Fortunatis insulis co[m]mentariolis . . . Accessit Pervani regni chorographica tabula. Omnia figures in aes incises exprassa a Theodoro de Bry,* Frankfort, 1596. The figure shown is from the first German edition of 1597.

CATAWBA INDIAN POTTERY: FOUR COLORS AND A MIRACLE OF SURVIVAL

The *Ninth Key* of Basil Valentine [Figure 40(b)] describes four colors of trans-mutation in the Great Work: black, white, citrine (a yellow) and ultimately red, symbolized by the crow, swan, peacock, and phoenix, respectively. It is interesting that these are the four characteristic colors of earthenware fabricated for thousands of years by aboriginal peoples in diverse lands.

The Catawba Indians located in South Carolina spoke a Siouan language.[1] They were a once powerful nation that alternately coexisted and fought with the Cherokees in the Carolinas. However, as of June 1908, only nineteen houses and ninety-eight Catawbas were counted on the reservation and in its surroundings in York County.[2] Although pre-Columbian Catawba pottery was largely utilitarian (cooking pots, water jugs), starting in the eighteenth century it became a source of hard currency for the Indians. They began to fashion objets d'art in addition to traditional pieces. These were often taken to the port city of Charleston, South Carolina, traded, and sold. The very survival of Catawba culture came to depend to a significant extent on the sale and trade of pottery, largely fabricated by women.[3–5] This is elegantly stated by former Catawba Tribal Historian Tom Blumer:[3]

> [T]he Catawba pottery tradition has survived for over 4,500 years. That it has done so is a tribute to the tenacity of the people who make up the Catawba Nation and the power of pottery, as an art form, to define that Nation and help it endure. It is a miracle of survival that will take the Catawba to the Third Millenium and beyond.

Figure 35 (left) shows a mostly reddish-brown headed bowl with three running legs made by Master Potter Sara Ayers (1919–2002).[3,5] The legs are off center, and the broken symmetry provides a wonderful dynamic to the piece. Also shown in Figure 35 (right) is a two-headed, fluted bowl made by young master Monty ("Hawk") Branham (b. 1961). The heads were ultimately derived from a mold made over 100 years ago by the great Martha Jane Harris. These pieces are made almost the same way they were in prehistoric times. Clay is dug

FIGURE 35. ■ Two pieces of Catawba Indian pottery: left, two-headed fluted bowl with three "running" legs by master Potter Sara Ayers; right, two-headed, fluted bowl by young master Monty ("Hawk") Branham. Catawba pottery is still made essentially as it was 4500 years ago. [Photograph by Thomas W. ("Wade") Bruton.]

from holy and secret sites along the Catawba River which contain rich deposits of kaolinite, sifted, mixed, and dried in the sun and rolled and pounded to remove air pockets. Clean kaolinite is fluffy and white. Pipe clay has organic matter and is heavier. The two are usually mixed to make a pot. Larger pots are built using layers of coils of clay that are shaped and smoothed, then allowed to dry. A pot may be incised with symbols just before being totally dry and, when dry, it is laboriously burnished with smooth river stones that have usually been passed between generations of women. The pots are then wood-fired in pits in the ground, removed, and allowed to slowly cool. Open-pit firing is considered to be low temperature (1200°C or 2200°F) or soft firing as opposed to hard firing (1450°C or 2650°F).[6] Air pockets in the clay and even slight wind gusts often cause a high degree of breakage. The high shine in the finished product is due to hours of burnishing rather than to glaze, which is never used. Clay pots, which are unglazed, are not considered suitable for holding water since they "sweat" and will stain furniture. However, one can imagine taking a water jug into the field—its sweating and vaporization from the surface will cool the bulk of the water inside. Furthermore, the frequent heating and decomposition of fat as well as protein from sinew and meat will coat the inside of a cooking pot and seal it.

The colors in this pottery are largely due to the iron so abundant in all clays.[6] Iron is the fourth most abundant element in the earth's crust. It is largely found in the iron(II) (ferrous) or iron(III) (ferric) oxidation states. Iron(II)oxide (FeO), iron(III)oxide (Fe_2O_3, hematite), and ferroferric oxide (Fe_3O_4), which contains both Fe(II) and Fe(III), are the three oxides of iron commonly encountered. The mottled coloring of the pot depends upon the degree of oxidation and also reflects the smoke and soot of the wood employed in firing since different woods burn at different temperatures and oxygen levels.[7] One of my former professors at Princeton University, Tom Spiro, called the color changes associated with "tweaking" the environments of transition metals, such as iron, "tickling electrons." Under oxygen-rich conditions, the dominant colors are "white" (really buff), and yellow and red and are due to a greater abundance of Fe(III). Oxygen-poor conditions can be achieved by "smother-burning" pots by surrounding and covering them with wood. The presence of carbon monoxide (CO) causes more reducing conditions conducive to enrichment in Fe(II). This is the way to deliberately produce a shiny, black pot; otherwise, coloring is left largely to the fates. Traces of manganese also help to blacken pots as will soot.[7] When removed from the fire, the pieces are usually dark and then lighten as they cool. Dynamic chemistry is occurring, for example, disproportionation of FeO to Fe_3O_4 and Fe although Fe will further oxidize.[8] Sometimes a greasy-looking area can be seen on the surfaces of the pots. This is probably due to local vitrification perhaps by a local concentration of feldspar or mica.[6]

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