How to See a Diagram:
A Visual Anthropology of Chemical Affinity

*by Matthew Daniel Eddy**

ABSTRACT

In 1766, Thomas Cochrane entered the Edinburgh classroom of Joseph Black (1728–99) to learn chemistry for the first time. Cochrane was studying medicine, and, like so many of Black's students, he dutifully recorded several diagrams in his notebooks. These visualizations were not complex. They were, in fact, simple. One of them, reproduced in this essay, was a single "X," a chiasm. Black used it to illustrate ratios of chemical attraction. This diagram is particularly important for the history of chemistry because it is often held to be the first chemical formula, and, as such, historians have endeavored to explain why it was unique and how Black invented it. In this essay, I wish to turn the foregoing premise on its head by arguing that Black's chiasm was neither visually unique nor invented by him. I do this by approaching a number of his diagrams via a visual anthropology that allows me to examine how students learned to attach meaning to patterns that were already familiar to them. In the end, we will see that Black's diagrams were successful because their visual simplicity and familiarity made them ideally suited to represent the chemical theories that he so skillfully attached to them.

> The Existence of Chymical Arts is nothing else but the Existence of Chymical Knowledge. —Joseph Black[1]

> Treating diagrams as things in themselves means giving up the notion that they are simply abstractions of reality, stripped down versions of the world of experience.
> —John Bender and Michael Marrinan[2]

> The arrow points only in the application that a living being makes of it. —Ludwig Wittgenstein[3]

> [Visualizations] capitalise on human ability to make rapid inferences about space and the things in it . . . and to perform mental transformations and operations on objects in space.
> —Barbara Tversky[4]

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[1] Joseph Black, *Notes from Dr. Black's Lectures on Chemistry 1767/8*, Thomas Cochrane (Notetaker), ed. Douglas McKie (Cheshire, 1966). Hereafter cited as Black (1767/1966).

[2] John Bender and Michael Marrinan, *The Culture of Diagram* (Stanford, Calif., 2010), 19.

[3] Ludwig Wittgenstein, *Philosophical Investigations*, trans. G. E. M. Anscombe (Oxford, 1967), 454.

[4] Barbara Tversky, "Communicating with Diagrams and Gestures," *International Conference to Review Research on Science, Technology and Mathematics Education* (2007), 111–23, on 111.

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VISUAL ANTHROPOLOGY

The forms and meanings of early modern teaching diagrams have remained largely unexamined by cultural historians. This situation, however, is slowly changing, especially in light of work that treats scientific diagrams as pictures.[5] In addition to this, the growth of digital culture in recent years has slowly begun to erase the division hitherto drawn between timeless works of art and everyday pictures. Instead of being seen as sedentary objects that exist outside time and space, pictures are now seen as objects that were recognized, made, and circulated in many ways that required different modes of access.[6] In this chapter I wish to build on this notion of a picture by focusing on the role played by the visual order of diagrams in the world of early modern chemical knowledge.

My aim is modest in that I merely wish to dig a bit deeper into the design of useful chemical pictures. I am interested in the diagrams inscribed and studied by the hundreds of students who attended Joseph Black's lectures at the University of Edinburgh during the last three decades of the eighteenth century. We know these diagrams were useful because they were copied over and over again by students taking his course. Indeed, they not only wrote them in the rough notebooks that they took in his lectures; they also redrew them in the bound, recopied notebooks that they made at the end of the course.[7]

The history of chemistry has tended to treat the diagrammatic tables and formulas used by Black and his contemporaries as fixed entities. The recent work on the visual anthropology of diagrams used for scientific teaching or research, however, has shown that their designers did not see them as timeless abstractions and that their meaning was strongly influenced by the direct interface between natural knowledge and visual culture. As intimated in the work of the social anthropologist Tim Ingold, the lines of graphic compositions, like diagrams and tables, are shaped by wider epistemic processes and cannot be disentangled from the beliefs of those who used them or the reasons why they were made.[8]

[5] Scientific diagrams are treated as pictures in Julia Voss, *Darwin's Pictures: Views of Evolutionary Theory, 1837–1874* (New Haven, Conn., 2010); and Tim Ingold, *Lines: A Brief History* (London, 2007). See also the diagrammatic insights of pictures given in Michael Baxandall, *Painting and Experience in Fifteenth-Century Italy* (Oxford, 1972); Eugene S. Ferguson, *Engineering the Mind's Eye* (Cambridge, Mass., 1992); and Edward R. Tufte, *Visual Explanations: Images and Quantities, Evidence and Narrative* (Cheshire, 1997).

[6] David Freedberg, *The Power of Images: Studies in the History and Theory of Response* (Chicago, 1989); Svetlana Alpers, *The Art of Describing: Dutch Art in the Seventeenth Century* (London, 1983); Martin Kemp, *Visualizations: The Nature Book of Art and Science* (Oxford, 2000).

[7] Black's affinity diagrams occur in most manuscript student notes taken in his lectures from the 1750s to the 1790s. My research is based on the many notes housed in the special collections of the University of Edinburgh, University College London, the Chemical Heritage Foundation in Philadelphia, and the Royal Society of London. Because citing all of these volumes would be impractical, I cite representative sets throughout this essay. The most accurate republication is Black (1767/1966). I cite the sections of these lectures relevant to the topics under consideration. A list of the collections that house manuscript copies of Black's lectures is given in William A. Cole, "Manuscripts of Joseph Black's Lectures on Chemistry," in *Joseph Black 1728–1799: A Commemorative Symposium,* ed. A. D. C. Simpson (Edinburgh, 1982), 53–69.

[8] Ingold, *Lines* (cit. n. 5); see esp. his chapter on evolutionary diagrams, 104–19. See also the visual anthropology of learning as addressed through the publications that emanated from Ingold's "Learning Is Understanding in Practice" project. These are listed on the project's Web site: http://www.abdn.ac.uk/creativityandpractice/ (accessed 1 February 2014). Ingold's work on this topic extends the visual anthropology of Walter J. Ong, *Ramus, Method and the Decay of Dialogue: From the Art of*

In recent years, the visual anthropology of diagrams has been explored by cultural historians of science like David Kaiser, Andrew Warwick, and Hans Jorg Rheinberger.[9] Rather than treating them as ethereal abstractions, these scholars frame diagrams more as a visual genre of representation anchored in both the material and intellectual skills possessed by the community that created or appropriated them. This approach has also been employed by early modern historians of scientific representation such as Sachiko Kusukawa, Sven Dupré, and Barbara Maria Stafford, who research the ways in which early modern diagrams were valued or understood by their users.[10] My view of graphic artifacts extends the work of these authors, especially since I treat diagrams as objects that moved through time and space in a manner that was a knowledge-making process.

In what follows, I present a visual anthropology of the Enlightenment diagrams that Black used to teach his students chemistry. Building on the epistemic concerns of Ingold and Rheinberger, I take the term "diagram" to mean a schematic picture intentionally designed to contain paths of information made from lines or symbols that are meant to represent natural events, objects, or processes. By taking this path, I treat diagrams as linear artifacts, as collections of marks in space, which represent concrete patterns of thought that were assembled and disassembled based on the needs of early modern students as users, and professors as designers.

PICTURING CHEMISTRY

The strong links between early modern chemistry and visual culture have long been recognized by intellectual historians. Studies on this topic tend to approach the chemical arts from either an iconographic or a functional perspective. Both of these traditions have their charms. The tools provided by iconology, for example, extend a rich tradition of motifs and forms that historians have used to examine both the literal and metaphorical nature of chemical imagery, with particular attention being given to the mnemotechnic montages of the hermetic tradition and, more recently, the presence of chemical imagery in portraiture.[11]

Discourse to the Art of Reason (Cambridge, Mass., 1958); and Jack Goody, *The Domestication of the Savage Mind* (Cambridge, 1977).

[9] For experimental diagrams, see Hans-Jörg Rheinberger, *An Epistemology of the Concrete: Twentieth-Century Histories of Life* (Durham, N.C., 2010); for Feynman diagrams, see David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago, 2005); for Newtonian diagrams, see Andrew Warwick, *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Chicago, 2003).

[10] Kusukawa, Dupré, and Stafford have numerous publications that are relevant to diagrams. For representative works, see Sachiko Kusukawa, *Picturing the Book of Nature: Image, Text, and Argument in Sixteenth-Century Human Anatomy and Medical Botany* (Chicago, 2012); Sven Dupré, "Visualization in Renaissance Optics: The Function of Geometrical Diagrams and Pictures in the Transmission of Practical Knowledge," in *Transmitting Knowledge: Words, Images and Instruments in Early Modern Europe,* ed. Sachiko Kusukawa and Ian Maclean (Oxford, 2006), 11–39; Barbara Maria Stafford, *Body Criticism: Imaging the Unseen in Enlightenment Art and Medicine* (Cambridge, Mass., 1993). For the epistemology of early modern diagrams, see also Bender and Marrinan, *Culture* (cit. n. 2); Tufte, *Visual Explanations* (cit. n. 5); Lorraine Daston and Peter Galison, *Objectivity* (New York, 2007), esp. chaps. 1 and 2, 17–114.

[11] The iconographic approach to chemical images has been addressed by a number of publications over the past few decades. For the connection between Jungian psychology and alchemical imagery, see William R. Newman, "*Decknamen* or 'Pseudochemical Language'? Eirenaeus Philalethes and Carl Jung," *Rev. Hist. Sci.* 49 (1996): 159–88. For the wider relevance and implications of the iconographic approach, see Lyndy Abraham, *A Dictionary of Alchemical Imagery* (Cambridge, 2001); and

By contrast, the functional approach focused on the pictorial aspects of chemical materials or graphemes. Studies from this tradition have taught us much about the visual qualities of substances, instruments, and graphic artifacts, like symbols, schemata, and formulae, with the emphasis being placed on how such images were used within experimental settings. Yet, despite their conceptual differences, the temporal and spatial modes of analysis that underpin the iconographic and functional approach are very similar.[12]

Both tend to trace an image through time by attaching it to a specific idea or thinker. Likewise, both tend to bracket the communal conceptions of graphic space that affected how the image was preserved, modified, or valued. This means that, although a visual anthropology of early modern chemical imagery is starting to emerge in the work of scholars like Ursula Klein and Jennifer Rampling, we are only just beginning to understand how the pictures of early modern chemistry were used and iterated, or, more fundamentally, how the skills and routines required to use them were learned.[13]

Bearing its infancy in mind, the visual anthropology of early modern chemical diagrams is probably best seen as a mode of analysis that can be used in addition to, not in place of, the tools offered by iconologists and functionalists. My starting point for early modern chemistry professors like Black is the notion that they treated their pictures as things that were recognized as images, valued as objects, and made through media.[14] Such a perspective transforms early modern chemical diagrams into pictures that were composites of visual concepts, materials, and practices. In this sense, a "compositional" view of pictures is one that provides a way to recover the visual epistemology of Black and his students.[15]

There are many directions in which this compositionalist view could possibly lead us; however, I wish to examine how Black's visualizations were understood and pre-

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Christoph Lüthy and Alexis Smets, "Words, Lines, Diagram, Images: Towards a History of Scientific Imagery," *Early Sci. Med.* 14 (2009): 398–439.

[12] Perhaps the most influential exemplar of the functional approach to the representation and meaning of (al)chemical instruments and graphemes is the work of J. R. Partington, esp. *A History of Chemistry* (London, 1970), vols. 1–4. For a functional analysis of diagrams related to the affinity concept, see Alistair Duncan, *Laws and Order in Eighteenth-Century Chemistry* (Oxford, 1996).

[13] Ursula Klein and Wolfgang Lefèvre, *Materials in Eighteenth-Century Science: A Historical Ontology* (Cambridge, Mass., 2007); see esp. the many sections that address the graphic design and meaning of affinity tables. For chemical formulas and nomenclature, see Ursula Klein, *Experiments, Models, Paper Tools: Cultures of Organic Chemistry in the Nineteenth Century* (Stanford, Calif., 2005); its title notwithstanding, it addresses many issues relevant to the graphic representation of eighteenth-century chemistry. See also Jennifer M. Rampling, "Depicting the Medieval Alchemical Cosmos: George Ripley's *Wheel* of Inferior Astronomy," *Early Sci. Med.* 18 (2013): 45–86. A number of the visual issues raised by Klein and Rampling are also addressed in relation to nineteenth-century chemistry in Alan J. Rocke, *Image and Reality: Kekulé, Kopp, and the Scientific Imagination* (Chicago, 2010).

[14] This approach is influenced by the visual compositionalism of the art historian W. J. T. Mitchell, whose use of image, object, and media to define a picture is most clearly addressed in the initial chapters of W. J. T. Mitchell, *What Do Pictures Want?* (Chicago, 2005). His compositionalist approach to pictures is unpacked in Mitchell, *Blake's Composite Art: A Study of the Illuminated Poetry* (Princeton, N.J., 1992). The composite nature of pictures—in terms of both materials and forms—has long been underscored by art historians. See Baxandall, *Painting and Experience* (cit. n. 5); Alpers, *The Art of Describing* (cit. n. 6); Michael Camille, *Image on the Edge: The Margins of Medieval Art* (London, 1992). See also Svetlana Alpers and Michael Baxandall, *Tiepolo and the Pictorial Intelligence* (New Haven, Conn., 1994).

[15] By "visual epistemology" I mean the historical unfolding of the beliefs and values attributed to objects visualized by community. For more on this term, see the first chapter of Daniela Bleichmar, *Visible Empire: Botanical Expeditions and Visual Culture in the Hispanic Enlightenment* (Chicago, 2012). See also John Berger, *Ways of Seeing* (London, 2008).

sented as a set of chemical pictures to university students, that is to say, a specific community of viewers. Following this line of thought allows us to see how treating a picture as a composite "thing" that existed in time and space yields a better understanding of its value and meaning. The pictures under discussion will be three core diagrams used by Professor Joseph Black to represent elective affinity, the influential eighteenth-century theory of material composition that appealed to forces of attraction and repulsion.[16] I focus on the iterations that appear in Black's own lecture notes and in the notes that students made in his lectures, and I highlight the visual skills and tools that were available to students educated in the Scottish primary and secondary school system.

The main forms of visual representation on paper in Scottish schools were pictures composed from either words or lines. Detailed illustrations did play a role, but, due to various economic and cultural factors, the average schoolchild's everyday exposure to visual culture on paper consisted mainly of words plotted as lists and tables. Students interested in learning a trade or going to university were also exposed to simple shapes like squares, circles, and triangles. Thus, when a student first crossed the threshold of a university classroom, a core mnemonic skill he had in his possession was the ability to memorize information that had been plotted along various lines arranged geometrically on the page.[17]

The skills of recognizing, reading, and inscribing visual patterns were practiced every day when Scottish children visualized both words and lines on grids in their school notebooks. The skill was reinforced by the fact that they were concurrently taught that straight lines and geometric shapes were visual examples of how ordered thought ought to work. If the mind's eye was like a lens, then rational thought was like a chain of ideas being paraded in a line across a screen. This metaphor was a common trope in Scotland where it was used to explain cognition, to justify pedagogy, and to chastise immorality. I have treated this topic at length elsewhere, but I am noting it here because I want to underscore the fact that Scottish pedagogy attributed great worth to the visual expediency of words and lines plotted in a simple and straight manner.[18]

Because Scottish sites of learning promoted rectilinearity as a virtue, there were

[16] A number of terms for affinity were used during the early modern period, including: attraction, sympathy, *rapport* (French), and *Affinität* (German). Terms used to describe the act of decomposition were repulsion, antipathy, division, and *partage* (French). The early history of the affinity concept is given in William R. Newman, "Elective Affinity before Geoffroy: Daniel Sennert's Atomistic Explanation of Vinous and Acetous Fermentation," in *Matter and Form in Early Modern Science and Philosophy,* ed. Gideon Manning (Leiden, 2012), 99–124. For the larger context, history, and meaning of the early modern affinity concept, see Ursula Klein, *Verbindung und Affinität: Die Grundlegung der neuzeitlichen Chemie an der Wende vom 17. zum 18. Jahrhundert* (Basel, 1994); Duncan, *Laws and Order* (cit. n. 12); Mi Gyung Kim, *Affinity, That Elusive Dream: A Genealogy of the Chemical Revolution* (Cambridge, Mass., 2003); Georgette N. L. Taylor, "Variations on a Theme: Patterns of Congruence and Divergence among 18th Century Chemical Affinity Theories" (PhD diss., Univ. College London, 2006).

[17] For the print and manuscript sources used to instill graphic knowledge in primary and secondary education in Enlightenment Scotland, see Matthew Daniel Eddy, "The Alphabets of Nature: Children, Books and Natural History in Scotland," *Nuncius* 25 (2010): 1–22; and Eddy, "Natural History, Natural Philosophy and Readership," in *The Edinburgh History of the Book in Scotland,* vol. 2, *Enlightenment and Expansion, 1707–1800,* ed. Stephen Brown and Warren McDougall (Edinburgh, 2012), 297–309.

[18] Matthew Daniel Eddy, "The Shape of Knowledge: Children and the Visual Culture of Literacy and Numeracy," *Sci. Context* 26 (2013): 215–45; Eddy, "The Line of Reason: Hugh Blair, Spatiality and the Progressive Structure of Language," *Notes Rec. Roy. Soc. Lond.* 65 (2011): 9–24. The impor-

many principles of graphic design that were used to arrange words and lines into pictures suitable for university classrooms. The most popular graphic principles of composite diagrams were proximity, symmetry, and contrast. Once words and lines had been arranged into a picture, students were taught to associate various visual relationships with the principle. I will discuss these associations in more detail below; however, at this point it would be prudent to lay out the basic form and importance of Black's affinity diagrams.

DIAGRAMMING AFFINITY

Black used tables and figures as diagrams in his lectures to represent experimental instruments or chemical attraction. His tables contained lists of substances or their properties. Perhaps the most well known is his affinity chart (fig. 1), but there were others as well, including tables that classified the effects of heat, acids, and alkalis. Overall, his figural diagrams came in two varieties.

The first portrayed experimental apparatus, and the second used geometric shapes to depict some sort of chemical reaction. His use of tables and figures is consistent overall with the kinds of visual illustrations that accompanied the chemistry or natural philosophy books cited in his lectures, or which he had studied as a student.[19] Likewise, the practice of using diagrams as teaching aids in university classrooms was common in Scotland. This was especially the case in Edinburgh's Medical School, where Black's colleagues distributed diagrams as handouts, drew on chalkboards, and hung large charts at the front of the classroom.[20]

When Black's diagrams are considered as a corpus, as a group of conceptually related pictures, a striking pattern emerges. Aside from his depictions of experimental apparatus, most of Black's diagrams were used to visualize some aspect of chemical affinity. This pattern is important to note because the affinity concept both explained and predicted the composition of experimental substances and provided the main theoretical underpinning of chemistry during the late eighteenth century. Indeed, for some philosophical chemists, the force of affinity was analogous to the force of gravity.[21]

In his lectures, Black, like most professors of the day, offered little insight into how he created these diagrams. Yet, when they are considered as pictures, it can be seen that he put a great deal of effort into designing three different diagrams that were conceptually unique but visually familiar. Conceptually, each diagram addressed a specific aspect of chemical affinity. Visually, each diagram exhibited a different shape.

tance of the graphic metaphor of the mind is raised more generally in Ingold, *Lines* (cit. n. 5) and, with reference to early modernity, in W. J. T. Mitchell, *Iconology: Image, Text, Ideology* (Chicago, 1986).

[19] We lack a definitive study on the chemical texts used by Black to write his lectures, but many of the authors who influenced him and his Edinburgh contemporaries are addressed throughout A. L. Donovan, *Philosophical Chemistry in the Scottish Enlightenment: The Doctrines and Discoveries of William Cullen and Joseph Black* (Edinburgh, 1975); and Matthew Daniel Eddy, *The Language of Mineralogy: John Walker, Chemistry and the Edinburgh Medical School, 1750–1800* (Aldershot, 2008).

[20] The uses of diagrams and figures in early modern Scottish anatomical and botanical teaching are addressed in Joe Rock, "An Important Scottish Anatomical Publication Rediscovered," *Book Collector* 49 (2000): 27–60; in H. J. Noltie, *John Hope (1725–1786): Alan G. Morton's Memoir of a Scottish Naturalist, A New and Revised Edition* (Edinburgh, 2011); and in Noltie, *John Hope, Enlightened Botanist* (Edinburgh, 2011).

[21] This point is intimated throughout Duncan, *Laws and Order* (cit. n. 12); and Donovan, *Philosophical Chemistry* (cit. n. 19).

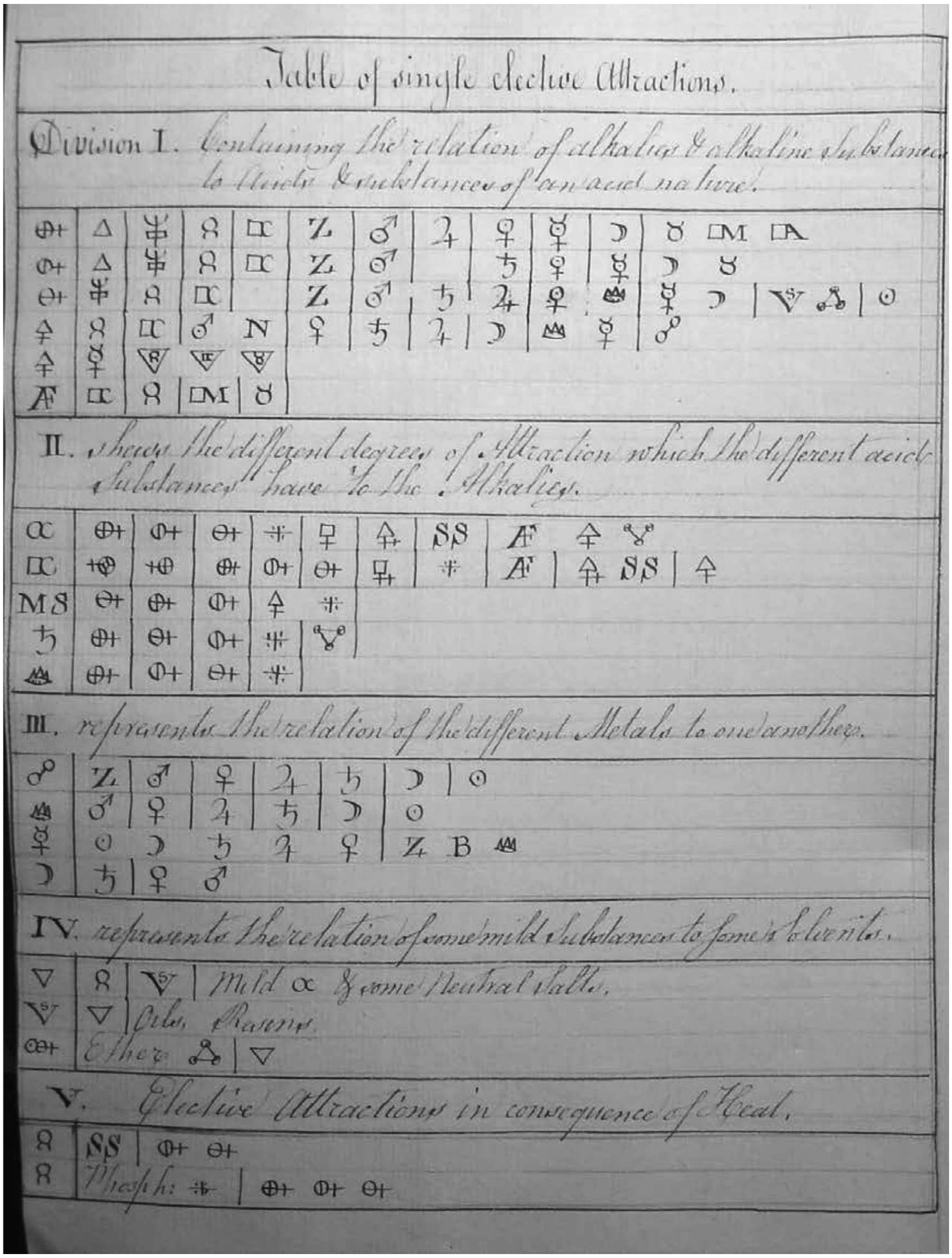


Figure 1. *Affinity table. Black,* A Course of Lectures, Volume 3 *(cit. n. 36). Black ordered his table so that it read from left to right. To use the table, a student needed to select a substance from the far left column and then read the entries listed in the row to the right. Each substance in the row was listed in descending order of attraction. Reprinted courtesy of the Royal Society of London.*

To achieve this visual differentiation, Black chose an X (fig. 2), a square-shaped table (fig. 1), and a circle (fig. 3). Additionally, he plotted headings within, around, or on these shapes, in a fashion that created a unique flow of information that required a distinctive reading pattern. Such differences required students to draw and use each diagram in slightly different ways, thereby making each one distinct and memorable.

Black fixed the visual patterns of his affinity diagrams during the 1760s, and they remained relatively similar for the rest of his career. In this capacity, they served as stable visual containers of chemical facts that circulated natural knowledge in Edinburgh and the many places where Black's students traveled or immigrated over the next half-century. In this sense, the diagrams provide an excellent example of a representational form that underpinned what Jim Secord once called "knowledge in transit"; that is to say, they were visible objects that circulated scientific information through Scotland's educational community and, more broadly, throughout the British Empire.[22]

Yet while the fixed structure of the lines served as an effective visual container, there was a certain degree of flexibility with the kinds of chemical knowledge that Black associated with the diagram at various points during his long career. Because he lived at a time when "chymistry" was rapidly changing, the conceptual malleability of his diagrams was a great asset because it allowed him to associate and dissociate information as required.

TABLING ATTRACTIONS

Many Scottish professors gave their students lists of facts and books. They also gave them lists of lecture titles called "headings." Next to these simple lists, the table was the most prevalent visual tool used on paper in Scotland's educational settings.[23] From a visual perspective, there were two formats: those with contour lines and those without. This was true for most tables of the time. Lineless tables were often presented in school textbooks and in various handouts used in Scottish universities to supplement lecture courses. Though they were arranged on a grid, their lineless internal structure allowed for the inclusion of full sentences.[24] Lined tables, on the other hand, usually contained more compressed information and placed more restrictions on the directional flow of the heads made available to its viewer.[25]

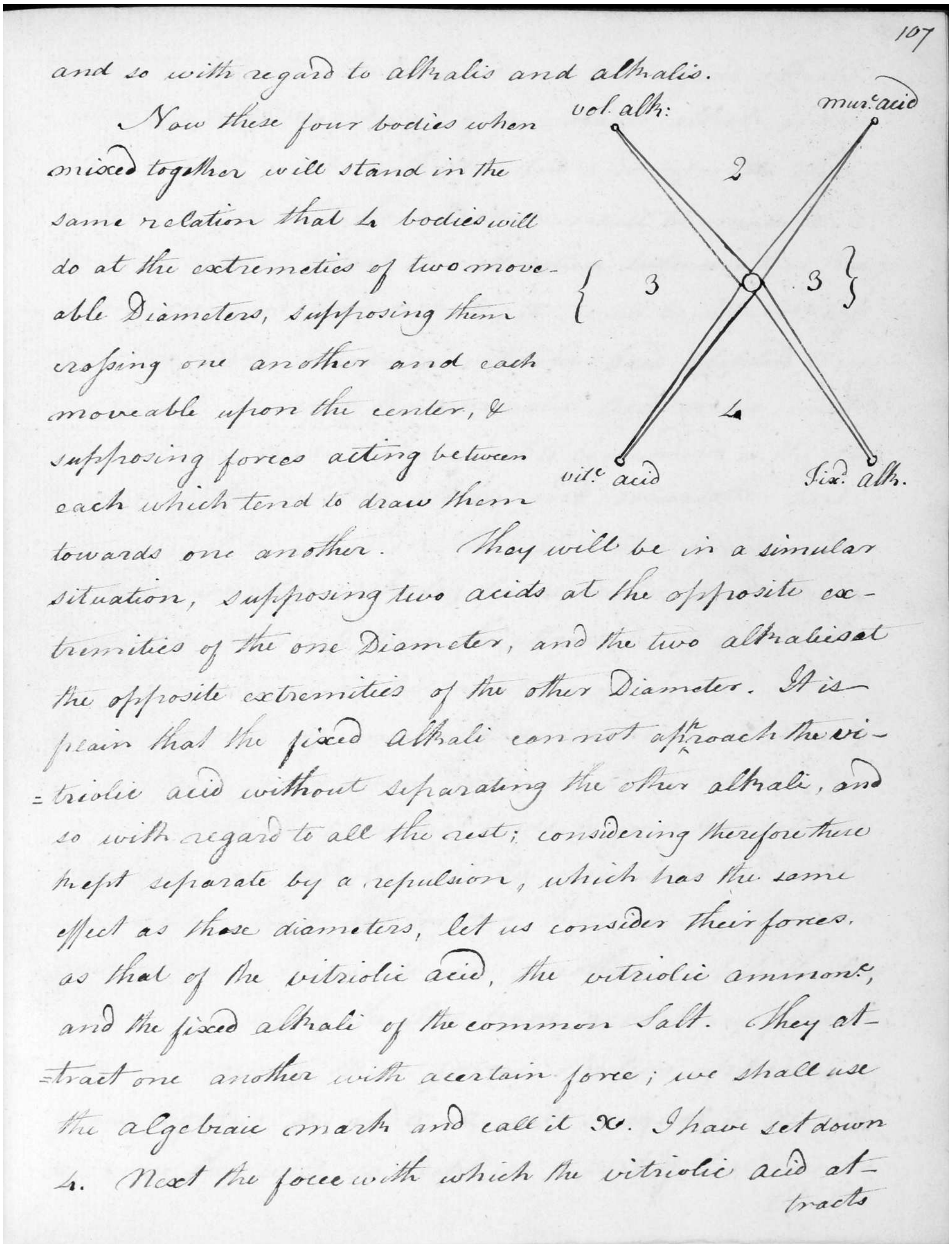
Black's affinity chart was a lined table (fig. 1). It consisted of an outer square and sets of internal crossed lines. This structure created a series of cells into which the pictographic heads of substances were placed and then read from top to bottom and left to right. Like the logarithmic tables used in natural philosophy courses, Black's chart was effectively a collection of lists that represented ratios of change.

[22] James A. Secord, "Knowledge in Transit," *Isis* 95 (2004): 654–72.

[23] See, e.g., the tables used in John Playfair, *Outlines of Natural Philosophy, Being Heads of Lectures Delivered in the University of Edinburgh* (Edinburgh, 1812), 1:160; or Alexander Fraser Tytler, *Plan and Outlines of a Course on Universal History, Ancient and Modern* (Edinburgh, 1782), 223–50. Oftentimes the only way to find copies of tables used by professors is to scour student notebooks.

[24] The graphic format of school textbooks and notebooks is given in Eddy, "The Shape of Knowledge" (cit. n. 18). There is no secondary research on the graphic nature of Scottish lecture heads. For a sample, see the following sets: John Walker's mineralogy lecture heads, *Classes Fossilium: Sive, Characteres Naturales et Chymici Classium et Ordinum in Systemati Minerali* (Edinburgh, 1787); John Hill, *Heads of Philological Lectures, Intended to Illustrate the Latin Classicks,* 2nd ed. (Edinburgh, 1785); Adam Ferguson, *Institutes of Moral Philosophy* (Edinburgh, 1769).

[25] A depiction of one of Black's acid-alkali tables is re-created in Black (1767/1966), 48.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and so with regard to alkalis and alkalis.

Now these four bodies when mixed together will stand in the same relation that 4 bodies will do at the extremeties of two moveable Diameters, supposing them crossing one another and each moveable upon the center, & supposing forces acting between each which tend to draw them towards one another. They will be in a simular situation, supposing two acids at the opposite extremities of the one Diameter, and the two alkalies at the opposite extremities of the other Diameter. It is plain that the fixed alkali cannot approach the vitriolic acid without separating the other alkali, and so with regard to all the rest; considering therefore these kept separate by a repulsion, which has the same effect as those diameters, let us consider their forces, as that of the vitriolic acid, the vitriolic ammon:, and the fixed alkali of the common Salt. They attract one another with a certain force; we shall use the algebraic mark and call it x. I have set down 4. Next the force with which the vitriolic acid attracts

Figure 2. *Chiastic affinity diagram. Joseph Black,* Lectures on Chemistry*, vol. 3 (1778), Paul Panton (Note-Taker), Bound MS, Chemical Heritage Foundation, QD14 .B533 1778, fol. 107. Black used a chiasm to visualize the hypothetical strength of the forces acting in chemical reactions. For example, if a fixed alkali (bottom right) was placed in contact with vitriolic acid (bottom left) and muriatic acid (top right) at the same time, it would elect to combine with the vitriolic acid, the reason being that fixed alkali was "more" (a force represented by a 4) attracted to vitriol and "less" (a force represented by a 3) attracted to muriatic acid. Reprinted courtesy of the Chemical Heritage Foundation.*

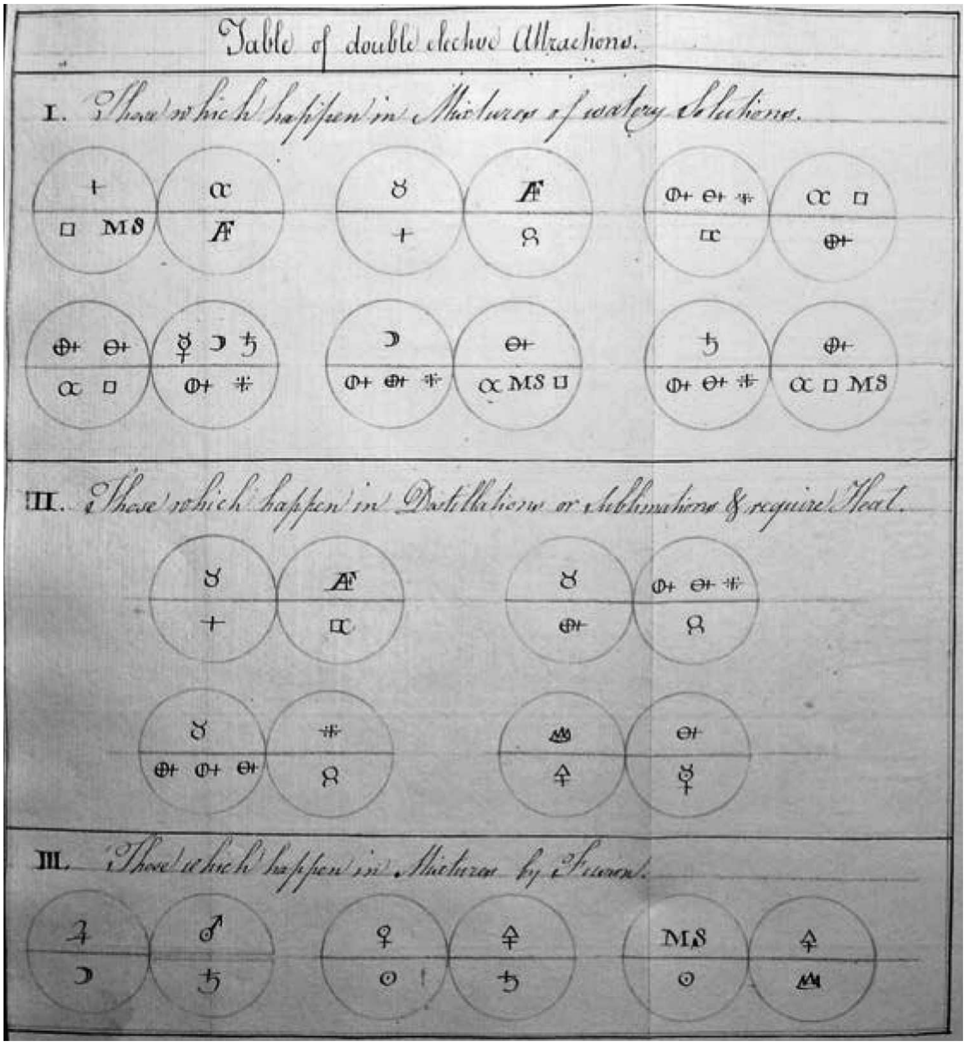

Figure 3. *Circlet diagram. Black,* A Course of Lectures *(cit. n. 36). Black used a double circlet diagram to visualize the double elective reactions taking place between the substances in two compounds. Take, for example, the first diagram in Part III of the table above (at the bottom left). The compound in the left circlet is a mixture of tin (on the top) and silver (on the bottom). The compound in the right circlet is a mixture of iron (on the top) and lead (on the bottom). Black explained the double elective attraction between the substances in these compounds in the following manner: "A mixture of tin and silver is melted with [a] mixture of iron and lead. The tin will join the iron, and the silver attract to the lead"; Black (1767/1966), 165. Black only visualized the compounds used at the start of the reaction but not the compounds of the final products. Reprinted courtesy of the Royal Society of London.*

He used it to represent single elective attraction, the form of chemical attraction that was the simplest kind of affinity. The table explained how one substance "elected" to leave a compound and then unite with another substance for which it had a stronger attraction.

Although there are several elements that are unique to Black's chart, the graphic formula of its gridded structure and spatial relationships had played a central role in chemical teaching since the early decades of the eighteenth century, especially in the lectures of his teacher William Cullen (1710–90) in Scotland, and in the chemistry courses of teachers such as France's Gabriel François Venel (1723–75; fig. 4) and Sweden's Torbern Olaf Bergman (1735–84).[26] The diagrammatic nature of the table had existed since Etienne François Geoffroy initially popularized it at the beginning of the century.[27] Within this tradition, the affinities visualized on Black's table were robust representations in that they were modifications based on his own experimental program.

In addition to his affinity table, Black also gave his students smaller tables that represented a select group of chemical affinities or, in the case of temperature, a set of important measurements. The order of the headings in all of these tables (which could be words or numbers) operated on a simple principle of visual proximity. This principle associated nearness with sameness and farness with difference. In affinity tables, for example, nearness represented a stronger attraction and farness represented a weaker attraction. Or, for temperature charts, nearness to one pole of the column represented hotness, and nearness to the other pole represented coldness.

Taking note of this dichotomous principle of visual proximity, moreover, reveals the central role played by the affinity table in the oral component of Black's lectures. Most student notes record him as regularly saying that substances had a weak or strong attraction for each other. These adjectives have traditionally been interpreted merely as qualitative descriptions. When considered in light of the visual relationships depicted on the affinity chart, however, they prove to be ratios that correspond to the dichotomous poles of attraction represented in the column of each substance. He was, therefore, often referring his students to the chemical relationships on the affinity table when he mentioned a strong or weak single attraction during a lecture.[28]

Black's discussions of the theoretical component of single displacement reactions in his lectures, though tersely informative, were diffuse. They occurred as necessary when he wished to point out the theoretical basis of simple chemical reactions. The scattered and brief nature of his comments meant that there was not a specific place in his course where he addressed the affinity concept in a systematic manner. Rather than being an omission, however, the absence of such verbal explanations was compensated for by the presence of the visual relationships depicted on the table. Its col-

[26] For the use of affinity tables in Scottish teaching, see Georgette Taylor, "Marking Out a Disciplinary Common Ground: The Role of Chemical Pedagogy in Establishing the Doctrine of Affinity at the Heart of British Chemistry," *Ann. Sci.* 65 (2008): 465–86. For France, see Christine Lehman, "Innovation in Chemistry Courses in France in the Mid-Eighteenth Century: Experiments and Affinities," *Ambix* 57 (2010): 3–26. The pedagogical reaction to the affinity concept in Holland is addressed in John Powers, *Inventing Chemistry: Herman Boerhaave and the Reform of the Chemical Arts* (Chicago, 2012), 163–8.

[27] For a list of the published affinity tables that appeared from the 1720s to the 1790s, see table 4.1 in Duncan, *Laws and Order* (cit. n. 12).

[28] Attractions are discussed in the language of strong and weak in Black (1767/1966), 23, 33–5, 38, 39, 40, 41, 43, 59, 60, 61, 63, 79, 89, 118, 133, and 158.

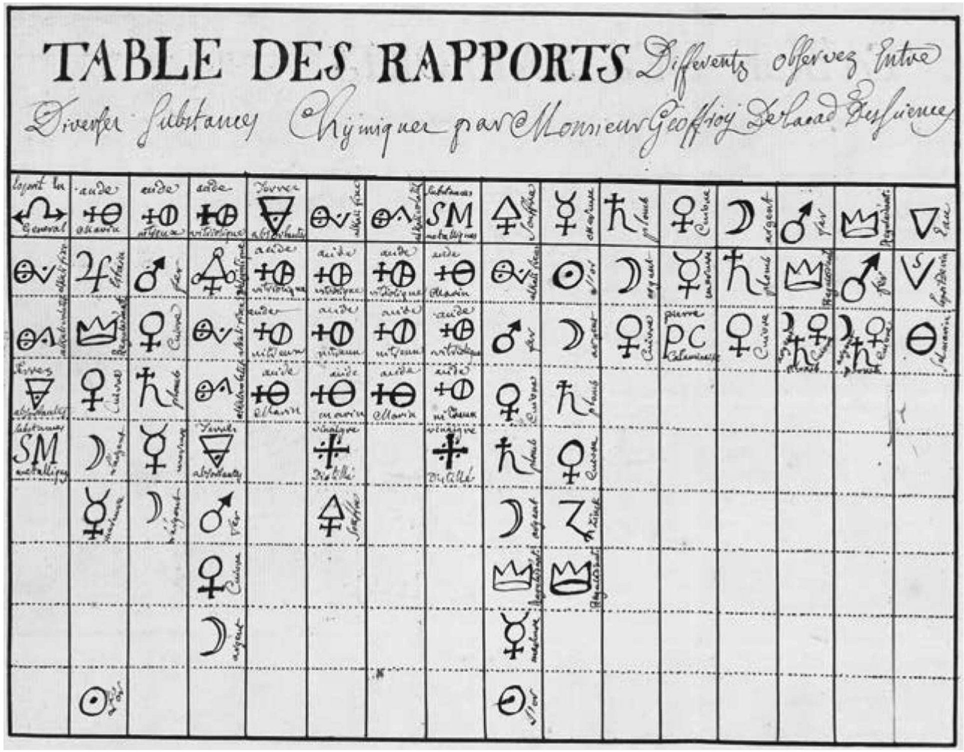

Figure 4. *Gabriel François Venel (1723–75), "Table des Rapports,"* Cours de Chymie*, Wellcome MS 4914. Reprinted courtesy of the Wellcome Library, London.*

umns and rows served as the most accessible and comprehensive representation of single elective attractions known to Black and the other chemists who influenced his thoughts on affinity.[29]

Black's lectures were an introductory course, so he tended not to discuss highly complex compounds or reactions. This explains why a large number of the experiments that he conducted in front of his students were single elective reactions. The single elective attractions depicted on Black's affinity table also constituted the most thorough summary on paper of the affinity concept given to students who took his course. Because of its pictorial nature, the table was not merely a simple reference tool but one of the central documents of the course in that it was the only place where his students could *see* a systematic overview of the affinity concept.[30]

Though explicit definitions of various aspects of affinity were sprinkled throughout his lectures, it was the table that gave his students a constant visual point of reference, and which allowed them to see easily a single elective reaction as one entry in a larger system of knowledge that was based on the theory of affinity. In giving this kind of conceptual priority to a graphic schema, Black was effectively saying that

[29] See the different kinds of affinity tables featured in Duncan, *Laws and Order* (cit. n. 12) and Klein and Lefèvre, *Materials* (cit. n. 13) for comparison.

[30] The same was true for students studying chemistry in eighteenth-century Paris. See Lehman, "Innovation in Chemistry" (cit. n. 26).

a pictorial mode of representation was more practical, and more accessible, than a verbal list of principles or rules of elective attraction. In short, pictures were more effective than words in this case.

CIRCLING COMBINATIONS

Black used two circles set side by side to visualize double elective attraction (fig. 3). Despite the fact that he used such "double circle" diagrams as teaching aids for the bulk of his career, they were not reproduced in the posthumous edition of his lectures that John Robison published in 1803.[31] Because Robison's edition served as the primary reference source for research on Black's ideas over the next two centuries, the meaning and importance of the circlets has remained relatively obscure. Of the studies that actually mention them, it seems that only a few recognize the fact that Black developed them solely to illustrate the concept of double elective attraction.[32] This being the case, it is worth explaining what the visual components of the diagram were supposed to represent.

The use of circlet structures as teaching aids in Scotland was, of course, not unknown. Unlike the ubiquitous presence of tables in Scotland's schoolbooks, freestanding circles were used primarily in geometry, or in subjects that built upon geometry such as gauging, cartography, or architecture.[33] The visual skills required to understand, to access, and to iterate such representations were then expanded at university. At the University of Edinburgh, for example, full circles, semicircles, and quarter circles were often used in mathematics, natural philosophy, and anatomy courses to depict the movement of matter through space (fig. 5).[34] Additionally, students in the arts faculty taking Alexander Tytler Fraser's course on universal history were given world maps that employed the common technique of setting the Eastern and Western Hemispheres side by side in two cartographic circles.[35]

Various approaches to using circles to represent natural knowledge, therefore, were present in the Scottish educational system and provided a good foundation on which Black could begin to build his circlet diagrams. Yet, despite this pedagogical advantage, Black was still faced with a particularly thorny visual problem that plagued early modern chemical knowledge as a whole. Whereas the objects of natural philosophy and anatomy were things like planets and body parts that were readily visible, the objects of chemistry, that is, chemical particles, were entities that had never been seen and had no prospect of being made visible in the near future. The circlets of Black's diagram were heirs to this problem and were not meant to be literal representations of material particles or their movements through time or space.

[31] Joseph Black, *Lectures on the Elements of Chemistry* (Edinburgh, 1803).

[32] An exception to this is M. P. Crosland, "The Use of Diagrams as Chemical 'Equations' in the Lecture Notes of William Cullen and Joseph Black," *Ann. Sci.* 15 (1959): 75–90.

[33] Alexander Ewing, *A Synopsis of Practical Mathematics* (Edinburgh, 1771); William Wilson, *Elements of Navigation: Or the Particular Rules of the Art* (Edinburgh, 1773). The graphic elements of these and other books are addressed in Eddy, "The Shape of Knowledge" (cit. n. 18).

[34] For examples of how this linear technique was used in lectures, see the diagrams included at the back of John Playfair's lecture heads, *Outlines of Natural Philosophy*, vol. 2, 2nd ed. (Edinburgh, 1816). See also the anatomical diagrams that Alexander Monro Secundus used in his anatomy course, which are depicted in the tables of his *Observations on the Muscles, and Particularly on the Effects of Their Oblique Fibres* (Edinburgh, 1794).

[35] Tytler, *Plan and Outlines* (cit. n. 23). For the circlet teaching diagrams used in the natural philosophy course of John Playfair, see his *Outlines* (cit. n. 34).

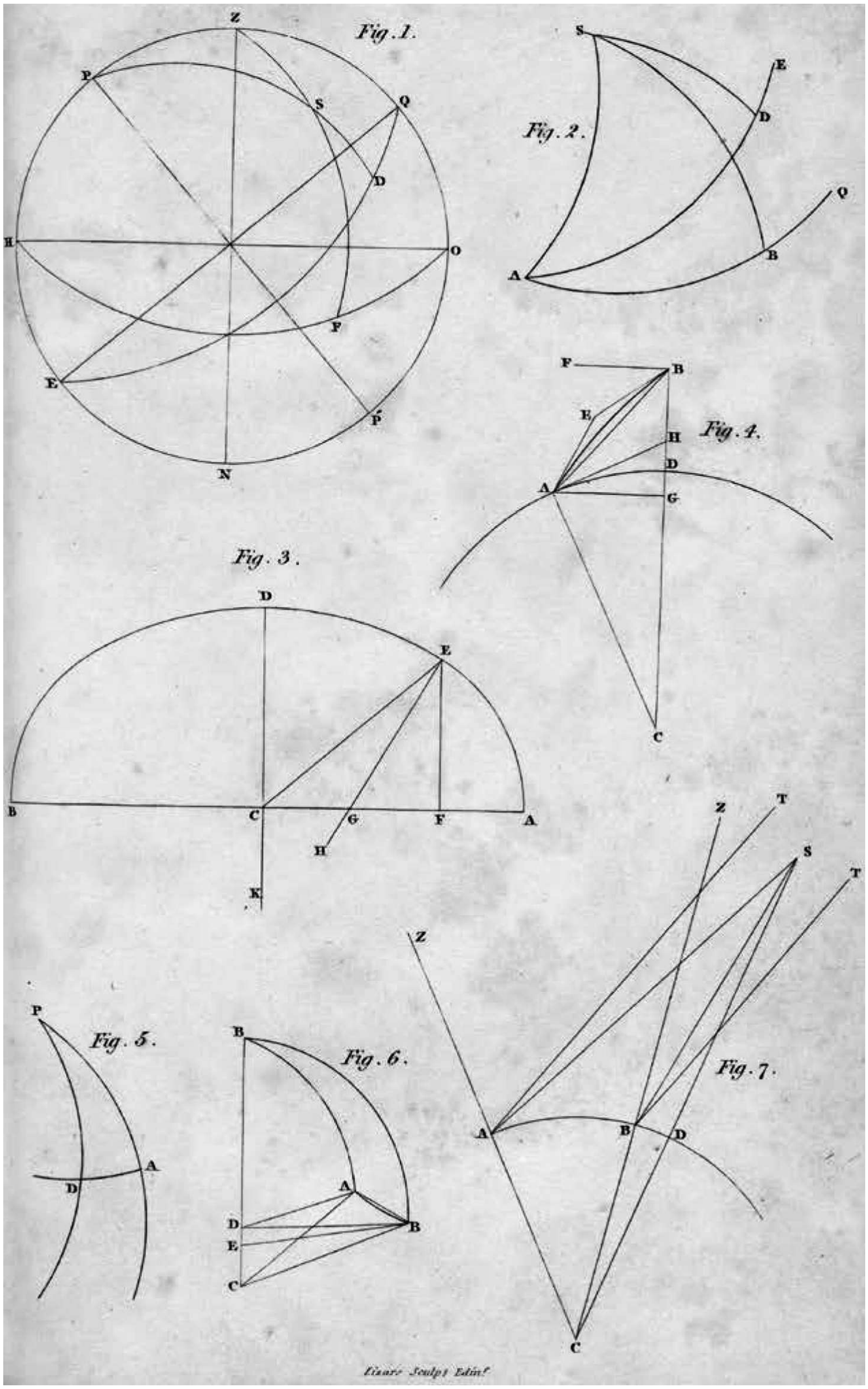

Figure 5. *Playfair,* Outlines of Natural Philosophy *(cit. n. 34), the first of four unnumbered plates that occur at the end of the volume. Huntington Library. Reprinted courtesy of the Huntington Library.*

Each circle represented a compound made of two substances. The 1782 lecture notes that Black read to his students state that the diagram of double elective affinity was "Composed of two circles, each of which is divided by a Horizontal Diameter."[36] Dividing the circles in this manner created four semicircles that Black used to represent four different substances participating in a reaction driven by double elective attraction. The reaction was a "double" attraction because each substance elected not to join another substance on two separate occasions. In this sense, it could also be seen as a double rejection because each substance rejected the other substance in its own circle, as well as another substance in the other circle.

In order to understand more precisely what Black intended his circlets to visualize, we need to ask how the structure and space of the diagram was supposed to be used by his students. Even though he employed circles to represent compounds, those who used the diagram were not meant to read it in a circular manner. Reading the diagram was very much a rectilinear affair. Black instructed his students to perform three visual moves. First, observe the compound in the left circle and then the one in the right circle (fig. 6). Second, associate the two substances in the upper semicircles and then do the same for the substances in the lower semicircles (fig. 7). Third, imagine the two new compounds.[37]

The relatively simple movements of the eye required by Black's diagram were not accidental. Indeed, they were designed. Black arranged the substances in a pattern that was more conducive to a simple reading. In other words, he stacked the visual deck. He did this by arranging the four substances in a symmetric pattern that vertically aligned those that he knew would combine into new compounds in the reaction. This arrangement minimalized the directional possibilities and allowed his students to concentrate on what they were supposed to be learning: the concept of double elective attraction.

What emerges from Black's visual decisions is the fact that he wanted each circlet diagram to be a self-contained picture that was sufficient to illustrate a multistep process. This is why he created one structure that could be read in two ways, depending on which directional path was used. In this sense, it was what anthropologists call a "multistable" image: pictures that offer "different readings in the single image."[38] Black was so keen to keep the design simple that he did not even offer a second diagram that visualized the final products of the reaction. Students simply had to imagine the products in their own mind.[39] This act of imagination was undoubtedly made easier by the fact that Black's circlets were schematic analogies of processes and not figural abstractions of corpuscular entities.

[36] This quotation occurs in the set of lecture notes that Black read to his Edinburgh chemistry students in 1782. Joseph Black, *A Course of Lectures on the Theory and Practice of Chemistry*, 3 vols. (1782), Bound MS, Royal Society of London, MS/147. The quotation occurs in the section on elective attractions in vol. 3, lecture 107. His conception of affinity and his use of his circlet diagram remained relatively consistent throughout his career. For an earlier account, see Black (1767/1966), 103, 454, 457.

[37] Steps 1 and 3 represent stasis, and step 2 represents change.

[38] W. J. T. Mitchell, *Picture Theory: Essay on Verbal and Visual Representation* (Chicago, 1994), 45–57. Multistep images that offer two primary readings are called dialectical images. Because Black's diagram has two major directional readings, it is a dialectical image. The anthropological significance of the kind of "multistability" raised by Black's diagrams is addressed in Tsili Doleve-Gandelman and Claude Gandelman, "The Metastability of Primitive Artefacts," *Semiotica* 75 (1989): 191–213.

[39] Following the work of Rocke, I take this historicized notion of imaginative practice to be akin to that which was required to make the "visually imagined microworld" of nineteenth-century chemistry. See Rocke, *Image and Reality* (cit. n. 13), xv.

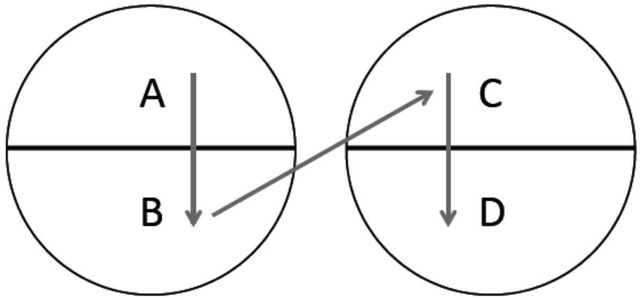

Figure 6. The first visual pattern required to read Joseph Black's circlet diagrams. Figure by Matthew Daniel Eddy.

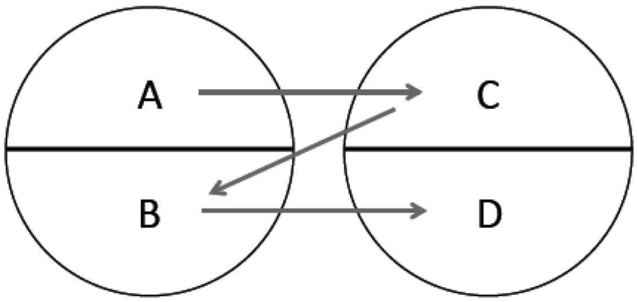

Figure 7. The second visual pattern required to read Joseph Black's circlet diagrams. Figure by Matthew Daniel Eddy.

Like the concept of single elective affinity, student notes seldom feature a section where the concept of double elective affinity is explicitly defined. Instead, the concept is mentioned as a matter of course after the introductory lectures. Most sets of student notes, however, contain drawings of circlet diagrams, and this indicates that, in addition to relying on a table to visually represent *single* elective affinity. Black also needed to use another visualisation to depict *double* elective affinity, a core theoretical component of the chemistry course. Unlike the affinity table, however, Black's circlet diagrams were usually accompanied by brief descriptions that explained what kind of double elective attraction was taking place in the picture.[40]

CROSSING RATIOS

Black's chiastic diagram depicted a double chemical reaction as well, but with a twist (fig. 2).[41] Rather than simply illustrating a qualitative change in substances, it also visualized a quantitative relationship between the forces of attraction that held the compounds together. It is this metric aspect of the chiasm that has attracted the attention of historians, particularly because it is seen as one of the first numeric approximations of chemical force expressed in an equation.

[40] More specifically, the three different kinds of double elective reactions represented by the circlet diagrams were: "I. Those which happen in Mixtures of Watery Solutions," "II. Those which happen in distillations or Sublimations & require heat," and "III. Those which happen in mixtures by Fusion." See Black (1767/1966), 164–5. Black addresses double elective attractions in passing on 49, 52, 59, and 67. Black's view of double elective attraction is addressed in Donovan, *Philosophical Chemistry* (cit. n. 19), on 216–8, and the diagrams of this kind of affinity, which preceded and followed him, are summarized in Duncan, *Laws and Order* (cit. n. 12), on 145–53.

[41] Black's chiasm occurs in most sets of student notes and in his notes. See Black (1767/1966), 274–9; Black, *Theory and Practice* (cit. n. 36), in vol. 3, lecture 107. For a 1770s version, see Joseph Black, *Lectures on Chemistry* (1776), transcribed by Paul Panton Jr., vol. 3, Bound MS, Chemical Heritage Foundation, Philadelphia, QD14 B533, fols. 107 and 493.

The chiasm had two visual zones. The outer zone ran around the tips of the chiasm and contained the abbreviated names of the four substances involved in a double elective reaction. The names or pictograms of the substances were inscribed at the end points of the chiasm as headings in the same visual footprint as those in the circlet diagram, and, hence, students could use the same directional path to read them. The inner zone, on the other hand, ran around the angles inside the chiasm. Each angle contained a number. Even if a student did not immediately grasp the meaning of the numbers, their close grouping at the center of the diagram showed that they were somehow related. When read solely as a group of numbers, the inner heads required a diamond line of sight.

Historians seeking to explain the visual origins of Black's chiasm have traditionally pointed to the lectures of his teacher, William Cullen, and Jean Beguin's popular seventeenth-century textbook entitled *Elemens de Chymie*.[42] The chiasms of these chemists were used to represent double attractions, and both positioned names or symbols of substances on the tips of the chiasm. Notably, both were used to teach students, many of whom were adolescents, which may explain why they were so visually simple. When compared to Black's chiasm, however, this simplicity in early modern chemical chiasms points directly to the visual absence of a conceptual piece of information.

Unlike the Cullen and Beguin diagrams, Black positioned numbers on the inner angles of the chiasm. Where did he get this idea? In order to see the origin of Black's inner zone of numbers, we must first remember the intended users of the diagram, most of whom were Scottish students trained in Scottish schools by Scottish tutors and teachers. In Scotland's mathematical tradition, children were taught a mathematical visualization, a trick, called the "Casting of Nines" or "Casting out the Nines." It was a calculation performed to double-check the answers of large arithmetic equations.[43]

The Casting of Nines is not used very often today, but, when it is employed in twenty-first-century classrooms, the numbers of the computation are lined up in a column.[44] Crucially, in early modern Scotland, this calculation was laid out on a chiasm, a practice that most likely originated from its long-standing use in the dichotomous Ramistic tradition of graphic spatialization.[45] An excellent example of this kind of diagram can be found in the marginalia written by the children of the Erskines of Torrie, Scotland, in the books of the family library during the middle of the eigh-

[42] The Cullen connection was addressed in print as early as 1803, when John Robison included a reproduction and description of the diagram in Black's *Lectures* (cit. n. 31), 544–6. The basic conceptual connection between the chiasms of Black, Cullen, and Beguin are addressed in Crosland, "The Use of Diagrams" (cit. n. 32). The graphic context and history of Beguin's chiasm is addressed in Alexis Smets, "Le concept de matière dans l'imagerie des chymistes aux XVIe et XVIIe siècles" (PhD diss., Radboud Univ. Nijmegen, 2014).

[43] The casting of nines was explained in Panton's popular mathematics text used in many Scottish schools. See William Panton, *The Tyro's Guide to Arithmetic and Mensuration* (Edinburgh, 1771), 23–4. The context of its usage is given in Duncan K. Wilson, *The History of Mathematical Teaching in Scotland to the End of the Eighteenth Century* (London, 1935), 2, 31, and 85.

[44] The modern uses of "Casting of Nines" computation are given throughout Isaac Asimov, *Quick and Easy Math* (Boston, 1964).

[45] See the calculation chiasm in Petrus Ramus, *Petrus Ramus, Scholarum Mathematicarum Libri Unus et triginta* (Basel, 1569). The connection between the Ramist chiasm in this text and Beguin's chemical diagrams is addressed in Smets, "Le concept de matière" (cit. n. 42).

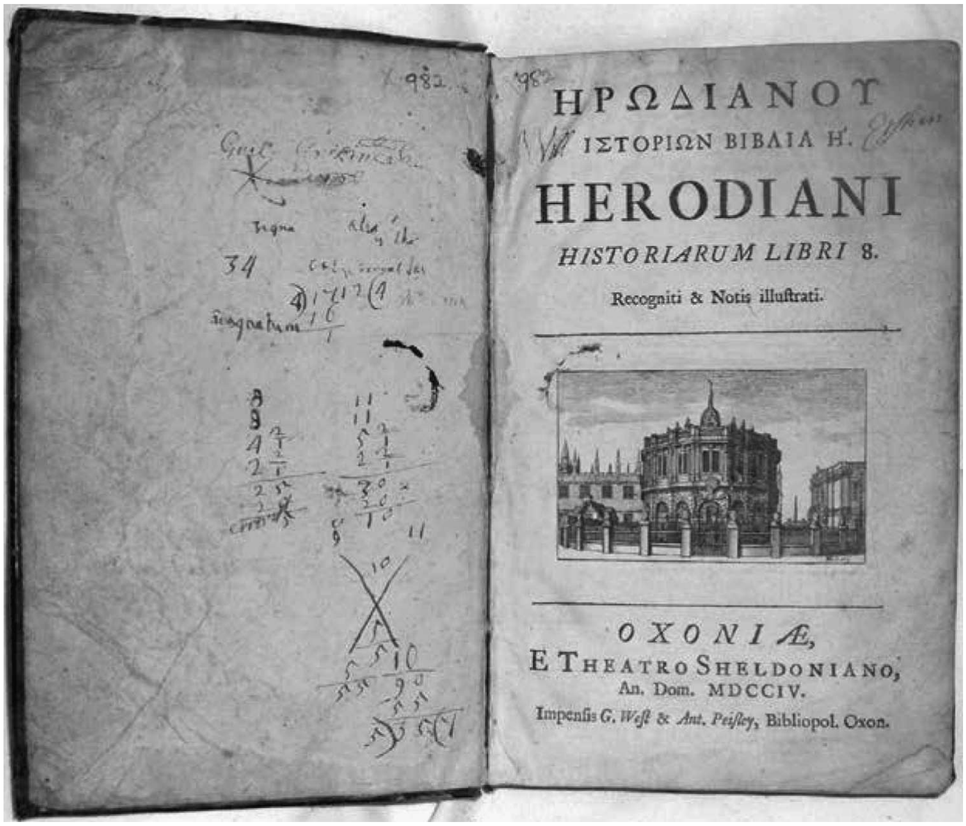

Figure 8. *"Casting of Nines" chiasm used by Scottish children to double-check multistep calculations. Drawn by one of the Erskine children living at Dunimarle Castle during the 1760s. Herodotus,* Herodiani historiarum *(cit. n. 46). Reprinted courtesy of Mrs. Magdalen Sharpe Erskine's Trust.*

teenth century (fig. 8).[46] The early modern version of the calculation consisted of several steps, and the answer to each one was placed on the inner angles of the chiasm. Thus, the visual origin of the inner zone of numbers that Black used for chemical ratios was a simple graphic tool used by schoolchildren that he probably selected because of its familiarity to his university students.

But what, specifically, were Black's numbers supposed to visualize? Stated simply, the numbers in each angle represented the ratio of attraction operating between the two corresponding substances fixed to the pinnacles of its outer zone. To use the diagram, Black instructed his students to pick a compound and then to look to the inner zone for the ratio of attraction between its two substances. If students wanted to read the next compound they simply cast their gaze back out to the tip of the chiasm and

[46] The Erskine chiasm appears on the endpaper at the front of Herodotus, *Herodiani historiarum libri 8. Recogniti & notis illustrati* (Oxford, 1704), Dunimarle Library, Banff, No. 982. The provenance of the eighteenth-century books from the Erskine family library is addressed in Friends of Duff House, "The Dunimarle Library at Duff House" (Duff House, 2011), leaflet available from the staff of Duff House, Scotland.

then performed the same angular reading that they had used for the previous compound. This kind of reading, moreover, could be performed in either a clockwise or a counterclockwise direction, and Black's discussions of the chiasm reveal that, depending on what he wanted to describe, he read the diagram in both directions during his lectures.

Crucially, Black's ratios did not represent any sort of real unit of measurement. He used them to conceptualize the relative attractions of the substances visualized in the diagram. The use of ratios in this matter was most likely taken from planetary astronomy, where they were employed by natural philosophers to compare the unitless planetary distances and perturbations of orbits. It was not until after astronomers had collected data during the 1761 and 1769 transits of Venus that an accurate distance between the sun and the earth was calculated, thereby allowing ratios to be expressed in known units of measurement (like miles).[47] Because those transits occurred during Black's lifetime, he probably saw his ratios in a similar manner, as formulas simply waiting to be activated with numbers in the event that a viable unit of chemical force was offered or proposed.

CONCLUSION

In this essay I have presented a visual anthropology of Joseph Black's chemistry diagrams with a view to investigating how they preserved and transmitted knowledge. When seen from this perspective, two important points emerge. First, the visual format of Black's diagrams had been used for a long time. This was especially the case for his chiasm, which was used in schools as a calculation tool. Second, Black's diagrams operated collectively as a visual system, an assemblage of pictures that all worked to explain the forces that attracted and repulsed substances. This means that the diagrams were designed to work together, and, as such, they constituted a unified attempt to visualize chemical affinity.

Far from being a unique occurrence, I have shown that Black's diagrams had a pedagogical history. Yet, if the diagrams were not explicitly unique, then what makes them noteworthy? The answer lies in the meaning that Black assigned to them. Whereas it is important to identify the form of simple images, such acts of identification alone offer little insight into how diagrams were used, what they were taken to represent, and how they comprised a unified visual system whose meaning was directly tied to a conceptual system. Likewise, it is very difficult to understand how the meanings of Black's diagrams—or most diagrams for that matter—were learned without taking their uses and iterations into account. So while the diagrams were certainly used to circulate knowledge in Black's classroom, the local use and meaning learned in that setting served as a guide to their global worth when they were taken outside Edinburgh.

[47] The exact ratio was not known in Black's lifetime. The precise distance was contested because of the "drop effect" that occurred when Venus first appeared in front of the sun. See Bradley E. Schaefer, "The Transit of Venus and the Notorious Black Drop Effect," *J. Hist. Astron.* 32 (2001): 325–36.