5 The Printing Press and Cryptography

Alberti and the Dawn of a Notational Epoch

Quinn DuPont

In the opening pages of *De componendis cifris* (1466), Leon Battista Alberti (1404–1472) introduced his famous "cipher wheel" while discussing the printing press.[1] In conversation with the papal secretary Leonardo Dati, Alberti noted how the newly invented "system of moveable type... brought us to similar appreciations… [of] strange characters with unusual meanings known only to the writers and receivers, called ciphers."[2] This reference to the movable type press is the first and only in all of Alberti's corpus.[3] But why would Alberti make reference to movable type in a cryptography manual? Kim Williams, the work's modern translator, suggests (on the authority of Anthony Grafton) that Alberti intended the story to function as a dedication, with the hope of having his work printed. This is not quite correct,[4] and either way, this reference to movable type is more complicated and important than either Williams or Grafton make it out to be. I will show that, instead, we have good reason to think Alberti's reference to the movable type press was a perfunctory admission that the invention of the movable type press had an impact on his thinking while developing his new form of cryptography. But how and why? What is it about the invention of the movable type press, still new and exciting in Alberti's day, that contributed to the development of the polyalphabetic cipher wheel?

In this chapter, I argue that both the movable type press and the cipher wheel utilized reproducible, modular, indexical, and combinatory forms of representation. In effect, the cryptographic technology Alberti developed was a new kind of writing, which offered unique capacities for technical representation. This representational invention departed from the ways that prior artistic and writing technologies worked, and it ushered in new ways of thinking about the world. Of course, Alberti was far from the first to design and use cryptography; before his invention, however, modes of expression were dominated by, and exemplified through, the oral and plastic arts, which were understood as "mimetic" or imitative. The invention of the movable type press was actually a first major step away from mimetic representation. The cipher wheel further refined and deepened how these representational logics were deployed, which was followed by numerous "code" machines.

Alberti's novel contribution was to recognize the latent capacities of the movable type press and to highlight the ways these capacities can be used for new kinds of representation. While printed text introduced new ways of thinking about the world and our ability to represent and understand it, cryptography went further by not only digging deep into the fabric of nature (in the sense of "decrypting" the Book of Nature) but also by harnessing "notational" strategies that keyed into natural identities, and formed new, artificial ones to enhance human control and dominion over the world. In doing so, Alberti inaugurated a "notational epoch." Of course, neither Alberti nor his followers saw the future so clearly, and their work (including developments in cryptography) continued to vacillate between ancient mimetic representational strategies and future notational ones. With considerable hindsight, we can see that Alberti's invention of the cipher wheel was one of the first significant technologies to "compute" the world, anticipating developments by Gottfried Wilhelm Leibniz, George Boole, and other figures traditionally considered part of the lineage of computing.

I explore Alberti's invention of the cipher wheel in the context of the movable type press to highlight the ways in which the material and representational bases of writing were reconfigured. Indeed, the histories of these cryptographic processes have unique pathways, captured in the logics of reproducible, modular, indexical, and combinatory forms of representation, and therefore leave to one side the theory of mimesis that originally led discussions of representation and eventually proved insufficient to explain the novel forms of representation. As Alberti discovered, polyalphabetic encryption, made possible by the cipher wheel, pushed representation and its operationalization through language to the breaking point, such that (in its extreme), encrypted text ceases to resemble the world at all and has no real meaning for its human originators (that is, it is not directly interpretable).

This representational reconfiguration, from writing to "plaintext" and "ciphertext," was perhaps best and first understood by Alberti, but Alberti was not limited to this single trajectory. Sometimes Alberti consciously drew on the ancient theory of mimesis, yet he also worked to overturn this traditional model, to develop notational technologies and explore their conceptual affordances.

The History of Notation and Cryptography

Alberti's *De cifris* was a major turning point in the history of cryptography, which historian David Kahn called the start of a "new species."[5] This work was also a major turning point for writing, as one of the first fully realized, practical examples of a working system of "notation." As I use the term, "notation" is an unambiguous, discrete set of marks (or utterances, etc.). A "notational *system*" includes the semantics of notational marks, as they either reach out to the world, or reach out to another sets of marks (in "indexical" or univocal ways).[6] Encryption, as Alberti realized, sets up a system of unambiguous, discrete marks (ciphertext) that indexically refer to other marks (plaintext), which in turn may refer to the world (as in the case of English writing), or not (as in the case of gibberish). And because the marks are indexical, the process can be reversed (encryption/decryption), without losing the "original" meaning.

Alberti described these notational mechanisms in *De Cifris*, using his design for a cipher wheel as an example of how to operationalize the technique. The cipher wheel is a mechanism that permitted easy realignment between the "index" key and a plaintext alphabet (being indexical and mutable). Analytically, the cipher wheel requires a notational system: a set of unambiguous, discrete marks that are aligned and realigned "semantically" (in the sense that the marks refer to, stand in for, or take on the "meaning" of other marks). Moreover, this "indexical and mutable" feature of the cipher wheel was essential to Alberti's fundamental "security" insight—by changing the index during encryption, multiple "alphabets" can be used, which greatly increases the complexity of the resulting ciphertext. This idea of changing the index during encryption is now called polyalphabetic encryption.

Alberti's work therefore required notation, and it marks an important chapter in the history of notation. However, the history of notation is still unwritten, despite its central importance for the development of mathematics and computation alike.[7] Here, I also explore a small but important chapter in the history of notation, which connects at multiple points to the larger history of cryptography (as the other works in this book show, the history of cryptography is also largely unwritten, but is starting to receive serious scholarly attention). By focusing on Alberti's technological developments, the conceptual refinement of systems of representation is also revealed. In this regard, Alberti was neither the first nor the last figure in the development of a broader "notational epoch," but he was at an important inflection point where notation began to take over from mimesis.

This phrase, "notational epoch," is critical to my description and therefore needs some explanation. I consider Friedrich Kittler's description of a "discourse network"—a configuration of the network of technologies and institutions in an epoch that allow "a given culture to select, store, and process relevant data."[8] This "discourse network," in fact, literally translates to "systems of writing down" or "notational systems" in Kittler's original German (*Aufschreibesysteme*). In his "Foreword" to Kittler's *Discourse Networks, 1800/1900*, David Wellbery notes that *Aufschreibesysteme* refers to a level of material deployment prior to questions of meaning; that is, the constraints that select an array of marks from the noisy totality of all possible marks.[9] The noisy totality of all possible marks, and the system of constraints that select them, are precisely the necessary conditions upon which encryption acts—selecting, transforming, and transmitting *from* the infinite variety of possible forms of expression *to* the potentially massive combinatory space of ciphertext. In other words, the notational epoch is a particular discourse network, made possible by socio-technical apparatuses (such as encryption technologies) that work *on but not through* mimetic representation (such as natural language or images).

The particular discourse network under consideration here, I argue, begins in 1466 when Alberti wrote *De cifris*, leading to the growth of a new species of cryptography. Indeed, this notational epoch cuts across those networks previously identified by Kittler (1800 and 1900), and is still very much in force today: we now deal with codes and their execution more than ever before, and increasingly, these codes are cryptographic.

Mimesis and Resemblance

Mimesis is the traditional theory of mediation. The history of mimesis reveals its connections first and foremost in the process of making art, but since it is a flexible theory of representation, it also works for many modes of expression. The key feature of mimesis is the duplication of perceived similarity and difference that links an expression to its object (or, in semiotic terms, between signifier and signified). As the theory of mimesis developed in response to changing artistic and technical practices, primarily through the late Middle Ages and early Renaissance, this function of duplication was replaced with repetition and resemblance.[10] Crucially, as I describe below, mimesis fails to adequately describe the particular way that technical media based on notation link subjects and objects.

The origins of mimetic theory are found in the shift from orality to writing. Speech was seen as more natural and more "present" than writing,[11] so the latter came to be seen as a kind of duplication of speech and oral expression. The most famous examples of mimetic expression are in Homer's epics, originally composed in an oral world. The formulaic feel of Homer's works is a consequence of being "stitched together" from standardized expressions (originally recited by "rhapsodes," a Greek term meaning "to stitch song together").[12] Additionally, because of this oral mode of composition, and the lack of writing at the time, Homer's work reflects an inherent mnemonic structure. Prior to writing, strategies for memory had to be an internal part of the expression, which is why Homeric expression includes mnemonic strategies, such as rhythm, repetition, addition, and redundancy.[13] That is, human expression and representation in oral cultures differed significantly from literate ones.

Plato lived while writing was still beginning to proliferate. Plato believed that speech was a duplication of more originary "forms," and writing doubly so. Because speech was seen as a duplication of a proper reality, Plato believed that a certain kind of distortion would often occur during oral expression, sometimes leading to the propagation of false and therefore immoral beliefs. This meant, according to Plato, that duplicative, or "mimetic" oral practices should be restricted. In fact, the followers of Homer are singled out by Plato in the *Republic* for promoting this bad kind of duplication. In Book III, Socrates and Adeimantus discuss the ideal composition of their proposed state, turning to the question of mimesis as a kind of performance or "story-telling."[14] Certain public discussions must be restricted, Socrates argued, because they would be liable to be imitated by the youth and thus bring about negative effects. Rather than revealing truth, the imitative effect forces the poet to "hide himself," and suggests a lack of mastery or skill, or failing to "achieve distinction."[15] Therefore, poetry, and all imitative arts should be restricted in both content and form.

In Book X of the *Republic*, Plato continues his discussion of how the origins of mimesis are irrational and illusory and of how the powerful imitative effect promotes troublesome personal and social behavior. In this book, Socrates argues that there are three levels of reality,[16] exemplified by the metaphorical makers of a couch: first, there is the idea of a couch, made by god—the "natural maker"—which is necessarily singular; second, material couches made by craftsmen who strive to be like god, imitating the original form but who do not "truly make [*poiesis*] the things themselves;"[17] and third, the imitative artists, such as painters, who do not imitate the original but simply imitate the (imitated) material works of craftsmen. To show how false and illusory the craftsman and especially the painter are, Socrates imagines a "clever and wonderful fellow" who walks around with a mirror and claims to be "making" all the things of the world as he points it toward objects.[18] This fellow with the mirror, obviously, is fabricating only the "appearance" of things, not their real form. Writing that imitates speech was thought to be like painting and therefore, according to Plato, failed to capture the true reality of things.

For Aristotle, the central concern of mimesis was *muthos* or "plot-structure," which offered a significant reimagining of Plato's theory of mimesis and led Aristotle to believe that mimetic practices were potentially beneficial. In Aristotle's *Poetics*, the "plot-structure" (*muthos*) drives narrative expressions not simply as the abstract shape of a plot but as the totality of the represented action with all its causal connections and development.[19] Aristotle argued that *muthos* was not simply the process of stringing together mimetic actions into a narrative but, rather, it hinged on good plot structure that must be "complete in itself, as a whole of some magnitude."[20] This "whole" must have a beginning, middle and end that are "naturally" connected. It is precisely the *muthos* structure that creates a feeling of completion, direction, and justifiable connection within a plot (versus a plot that lacks compelling features, zigging and zagging without reason). According to Aristotle, good plot-structure is created by mimesis' connection to reason, not (false) "inspiration" or madness, as Plato had argued previously.

While too sophisticated and various in their approaches to be described fully here—Plato opposing mimesis in favor of his own ontological approach, Aristotle seeing considerable value in mimetic arts through its channeling of *muthos*—ancient views of representation can be summarized as fundamentally configured around illusion and verisimilitude. As the ancients understood it, making art, and making representational expressions more generally, relied on a duplication of perceived reality through similarity and difference. After Plato and Aristotle, the question of representation, through the traditional theory of mimesis, developed further and came to stand in for the similar actions of repetition and resemblance. From the fall of Rome until the Renaissance, the Greek term and the original philosophical concept of mimesis fades somewhat, only to be replaced with an extremely rich semantic web of repetition and resemblances. As representation became a form of repetition, the theory saw that the "universe... folded in upon itself."[21] By the end of the sixteenth century, all aspects and offshoots of mimesis co-existed and interrelated in complex ways and became increasingly open to reform and revolution.

One of the most striking changes prior to Alberti's upheaval of mimesis came from the Catalan thinker Ramon Lull (1232–1315). In his *Art* (*Ars*), described over numerous works and revisions, Lull reconfigured the theory of representation that previously relied on the complex web of resemblances, as it had been handed down to him through ancient and medieval transmission. In his *Art*, Lull replaced the use of images with notation.[22]

Reflecting early concerns around the use of writing and its impact on memory, Lull's *Art* also sought to improve memory techniques. As Lull saw it, following Aquinas and other medieval thinkers, (mimetic) images had crept into the memory arts. (The memory arts were an ancient system, first elaborated by rhetors such as Quintilian, that enabled prodigious feats of memory.) Images were introduced as a way to fix items in memory and were thought to be efficacious because of their vivid (and therefore easily remembered) style of representation. However, drawing on Plato's critique of mimesis, Lull opposed the use of mimetic representations and developed a system that he saw as capable of aiding memory without using mimetic representation.[23] In place of mimetic images, Lull developed a system of clear and precise *notation* to help hold items in the memory.

In Lull's *Ars Brevis,* the first "figure" arranged the divine "dignities" (first causes) into two circles (or horizons), with each segment designated by a principle aligned against another.[24] The outer ring of nine letters

(B, C, D, E, F, G, H, I, K) aligns against the inner ring of dignities, arranged in *convenientia* (in the first figure, which is denoted by "A", the dignities are goodness, greatness, eternity, power, wisdom, will, virtue, truth, and glory). As the reader compares inner and outer circles, new prepositions are created, such as "goodness is great" and "greatness is good."[25] In figure four of the *Ars Brevis* (see Figure 5.1), Lull introduced a further ring while removing the names of the dignities, and he made the circles rotate against one another. With this tool, as the dignities rotated they revealed new connections for its user, who interactively explored the resulting predicates.

Each "dignity" could be combined according to particular rules, which amounted to a method for investigating reality. That is, this method was a way to do *work* and to actively investigate or "compute" the world, quite unlike existing memory systems that were static and merely held items in memory as *loci*. Lull's development of an active system using rotating wheels, with its particular history of representation, was an important precedent for Alberti's invention of the cipher wheel.[26]

Immediately following Lull's invention, many new code technologies emerged. It is within this context of mimesis and resemblances that Alberti designed his cipher wheel for polyalphabetic encryption. Ultimately, the practice of cryptography introduced new technical challenges, many of which were poorly captured by the flagging theory of mimesis. Guided by these technical challenges, cryptographers offered early critiques (and sometimes accommodations) to extant theories of representation. The raft of cryptographers who followed sometimes

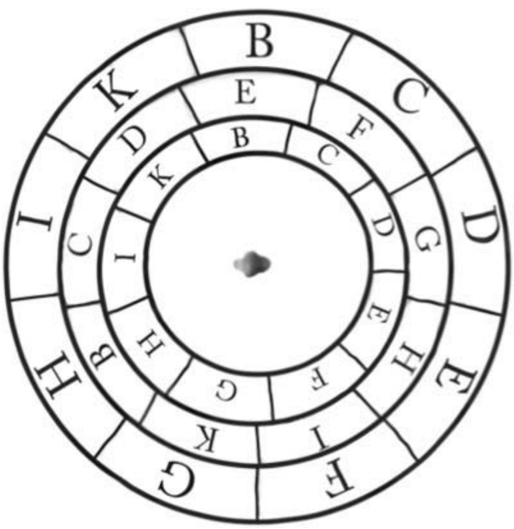

Figure 5.1 Reconstruction of the fourth figure, from Lull's *Ars Brevis*.[27]

also sought to remove resemblances, and their occult powers, from their cryptographic systems. In late Modernity, scholars like Descartes would continue to modulate mimetic theory, arguing that the category of resemblance should be removed entirely from modern epistemology, and scholars such as Leibniz would develop similar notational systems specifically for "computation."

Type and the Emergence of Plaintext

By the end of the fifteenth century, mimetic theory was undergoing rapid change as new technologies for communication, computation, and memory emerged. Alberti's notational innovations are an important part of this history, reflected in both his cryptographic and architectural work, which developed new kinds of ordering and modes of expression. Retrospectively, we can see that by leveraging the logics inherent in his notational innovations, Alberti was an impetus to the dawn of a new epoch in representational technologies. Prior to Alberti, one of the key technological advances in the fifteenth century was the invention of the movable type press, which, I argue, served as a prototype for Alberti's cryptographic system.

All of these systems relied on the transition from natural-seeming techniques and technologies for writing to the emergence of "plaintext," a token-identical form of writing that reflects a reality of the world as already divided into discrete marks, or one capable of being divided into discrete marks (that is, notation).[28] One important example of this trajectory is the history of "decryption" that followed the parallels between the Book of God (scripture) and the Book of Nature. As Peter Pesic has detailed previously, Francis Bacon's cryptological investigations, for example, took advantage of this perceived isomorphism.[29] Seeing that "decryption" could occur in already-textual sources, Bacon reasoned that with the right tools and training, the natural world could also be "decrypted." One of the key features of Bacon's method, however, was to reduce the smooth and continuous world, with all of its complexity, to a set of discrete marks. Bacon noted that the method could be reversed, too, utilizing his "bi-literal" cipher to signify "anything by anything" ("*omnia per omnia*").[30]

The key characteristics of these "plaintext" systems, shared by Bacon's bi-literal cipher, the movable type press, and Alberti's architectural and cryptographic systems, are that they deploy the logics of reproduction, modularity, indexicality, and combination. As I noted at the start of this chapter, Alberti mentioned the movable type press in *De Cifris* not only because the movable type press was an important technological precedent but because Alberti's cryptographic system further developed the implicit logics of the printing press.

Whereas the movable type press required external input for its use, Alberti's innovative cipher wheel worked "algorithmically" through its special design, as did an architectural plotting device he developed. Alberti's architectural works parallel his motivation in *De Cifris*, which attempt to develop new systems of representation not limited by mimesis. At many points in his architectural work, Alberti avoids drawing on mimetic styles of representation, such as by supplying *rules* (in the same way as algorithms) for all'antica construction, instead of drawings. In fact, according to Mario Carpo, throughout Alberti's entire architectural corpus there are no drawings of ancient monuments, nor even ekphrastic reconstructions. In this regard, Carpo believes, Alberti's architectural theory "cleanses itself" of the practice of "imitation," or mimesis.[31]

Alberti's Notation

In place of mimesis, Alberti utilized a "notational" form of representation when developing his novel machines. Like the movable type press that came before, these can be considered special "writing" machines. In *Descriptio Urbis Romae* (Figure 5.2), Alberti developed an ingenious device to plot the coordinates for a plan of Rome, which has significant parallels to his cryptographic invention in *De Cifris*.[32]

In an effort to avoid the issues involved in scientific and engineering communication that uses mimetic, visual descriptions, and the errors these methods potentially introduce, Alberti developed a tool to draw a plan of Rome. This tool used a list of points, which could be plotted. This special writing instrument—a kind of ruler pinned to the center of a circular horizon—matched notations on the ruler to notations along the circumference of the horizon. The plan of Rome is recreated by first

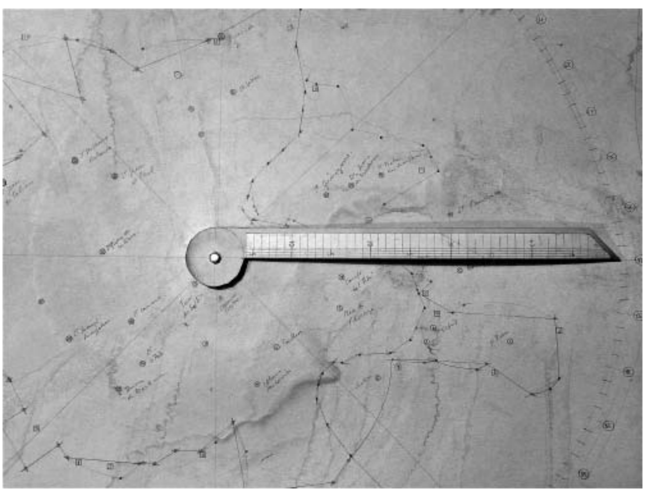

Figure 5.2 Reconstruction of Alberti's *Descriptio Urbis Romae* mechanism. Image used with permission of Patrick Thépot.[33]

plotting data points, and then, in a kind of connect-the-dots way, by drawing the outline.

Carpo calls Alberti's writing instrument a tool for producing "digital images."[34] Indeed, when his plotting machine (hardware) is combined with the appropriate method (software) and fed suitable coordinates (data) it produces "digital" images. In *De statua*, Alberti expands the scope of the mechanism, imagining its use in three dimensions as a way to re-present the human body.[35]

In *De Cifris,* Alberti described his cipher wheel, which could be used to produce polyalphabetic ciphertext (Figure 5.3). The cipher wheel is comprised of two rotating, circular planes that attach to a center pin or string, around which they rotate. Alberti stated that the disk is divided "into twenty-four coequal parts" which he called "houses;"[36] the smaller wheel of the cipher contains "mobile" houses. Together, the two wheels work like a formula (*formulam*), where the relative positions of the houses (the "index") are like a "key."

When the disk is rotated, a new indexical relationship (a "key") is established. The cryptographic "key" is set by aligning two letters: "say such k" Alberti writes, "lies under the upper-case B."[37] Substituting each letter of the plaintext to its "twin" along the other plane encrypts the message. When substituted, each letter comes to stand in for its twin, or comes to take on the "meaning" of the other letter, "thus a common letter, say A, will take on the meaning of another letter, say G...."[38]

It is important to note that if Alberti's desire to print *De cifris* had been realized (it was never printed in his lifetime), the transformation

Figure 5.3 The rotating horizons of Alberti's cipher wheel, attached by string.[39]

from <A> to <G> on the work's pages would have been in no way metaphorical. With movable type, an <A> can be literally replaced with a <G>. From the *material* of movable type to the (pre-symbolic, noisy totality) *real* of cryptography, the substitution <A> -><G> is indexical. That is, each letter's self-identity is required, but of course, unlike mimetic representation, visual similarity between <A> and <G> is not needed (in fact, in order to be considered notational, there must be an in-principle way of determining the difference between <A> and <G>).[40] The system works so long as any thing, natural language or otherwise, can be broken down into letters of plaintext, which are linked through an indexical relationship by the encryption transformation. This singular transformation, <A> -><G>, however, only produces single-alphabet encryption—a useful but marginally superior technology than what existed previously.

Alberti's cipher wheel is more than a handy mechanism for common substitution ciphers; the key cryptographic innovation is the use of multiple alphabets *in situ*. Alberti writes, "after I have written three or four words I will mutate the position of the index in our formula, rotating the disk let's say, so that the index k falls below the upper-case R."[41] By rotating the disk during the process of encryption a "new" alphabet is introduced with each rotation, making cryptanalysis significantly more difficult by increasing the combinatory space.

The reason why it is difficult to cryptanalyse polyalphabetic encryption is because natural languages have "natural" identities and redundancies, most noticeable in word and letter divisions, which are "scrambled" through polyalphabetic encryption by introducing new alphabets.[42] Each particular natural language, and indeed, each form of expression, brings about its own syntactical characteristics. These "natural" syntaxes are why it is possible to imperfectly remediate or translate natural languages. Alberti's cipher works precisely on these "natural" syntaxes. Specifically, he relates the intrinsic qualities ("*De notis literarris quales sese natura*")[43] of Latin letter "orders" to "numeric ratios" ("*numeri rationibus*"),[44] which naturally form vowels and consonants, bigrams and trigrams.[45] Alberti noted that, during encryption, these natural syntaxes (or identities) are first "scrambled" about, but like a dutiful caretaker collecting leaves blowing in the wind, cryptography then rakes the leaves into piles, forcing artificial identities and orders.[46]

Notational technologies like the cipher wheel or the plotting machine in *Descriptio Urbis Romae* offer a number of representational advantages over mimetic technologies. Before the widespread use of notational technologies, first explored with the movable type press, scientific and technical work was fraught with difficulty. Carpo argues that "the pre-typographical architect knew... long-distance transmission [using] images... [was] not a trustworthy medium," and "he practiced his craft within these limitations."[47] The problem with images is that when remediated or copied, errors are likely to creep in with each new copy. Notation, on the other hand, uses a small set of predefined marks (usually an alphabet), therefore less likely to introduce errors during copying, and has an unambiguous identity.[48]

There was also a great deal of economic, diplomatic, and scientific communication and commerce in Alberti's lifetime, requiring new, long-distance (and sometimes secret) transmission. This is why Alberti argued that cryptography was needed—secret, capable of long distance transmission (not as likely to be corrupted), and above all efficient (Alberti called it "commodious" [*scribetur commodius*]).[49] Additionally, in stark opposition to the prevailing forms of handcrafted reproduction and representation (painting, sculpture, carpentry, etc.), Alberti's technologies enabled mass production—mass production of built form (architecture) and mass production of writing (cryptography). Just as Alberti's architectural methods gave rise to "designed" buildings—in distinction to the old handicraft of architecture before him—his cryptographic methods offered order and precise forms of remediation. That is to say, Alberti was a champion of a new kind of "indexical" sameness, but not the sameness of mass production where every piece is identical, as though stamped out from a form or mold. It was the building blocks of letters printed from movable type presses that provided the model from which Alberti developed his notational machines, in architecture and cryptography.

The Printing Press Prototype for the Cipher Wheel

Returning to this chapter's initial provocation, what role did the invention of the movable type press have on Alberti's thinking, and how did this lead to a "new species" of cryptography and the dawn of a notational epoch? Movable type was invented in Alberti's lifetime and was influential to his thinking. Carpo calls Alberti the first "typographical architect,"[50] and the same can be said for his cryptographic work, also inspired by Lull's notational, combinatorial wheels. The invention of the alphabet originally brought forth the necessary identity configurations for writing to become plaintext, but it was the movable type press that made the functional aspects clear.[51] I argue that these functional aspects were logics of reproduction, modularity, indexicality, and combination. Like later computing and calculation machines, Alberti put these typographic logics to work in both his architectural and cryptographic apparatuses.

Reproducibility

The moveable type press changed existing notions of reproducibility. Like those before him, Alberti was familiar with the idea of reproducing identical copies from woodcuts, a pre-Gutenberg technique called xylography. Xylography produced whole "images," typically an etched picture, but sometimes the reproduction of a complete page including textual elements. Entire books—texts and images together—could, in fact, be printed using xylographic processes, but this "block book" process was rare and may have even originated *after* Gutenberg's invention, as a quick and cheap alternative to movable type. And more to the point, printing from woodcuts, while possible, had serious limitations. Because each successive "edition" introduced the chance of error, block book production was poorly suited for technical works of the sort Alberti was interested in.[52] In fact, the chance of copyist error for pictures was so high that authors typically wrote *textual* (ekphrastic) descriptions of what are fundamentally visual phenomena, such as architectural plans and forms.[53] Alberti was so worried about error that in his architectural works he requested copyists to write out numbers in longhand rather than using numeric symbols, even addressing the copyist directly in several cases.[54]

Avoiding the introduction of errors was one of the principle advantages of typographic expression for the reproduction of technical works. Traditionally, manuscripts were produced by scribes taking dictation. Scribes could be counted on to (somewhat) reliably replicate the correct order of a finite set of marks (alphabetic letters) that represent spoken words, but reproducing technical images and diagrams would have been very difficult. Etched woodblocks were one solution to ensure exact duplication for images, so long as the etching itself was correct, but these tended to get worn and broken over time.[55] For manuscripts, to duplicate a technical image was to invite critical mistakes.

Error propagation is also a real concern for cryptography. Alberti's polyalphabetic encryption "mixes" multiple alphabets with plaintext to result in a kind of "diffuse" ciphertext. So-called "diffusion" and "confusion" techniques are basic methods of encryption, as they frustrate cryptanalytic techniques by "hiding" plaintext more deeply within a combinatory space.[56] As Alberti realized, for any one letter of plaintext the corresponding ciphertext might be several letters, or mixed about in "unnatural" ways. On the other hand, the redundancy of natural languages permits transmission on "noisy channels," since redundant information accommodates errors. For cryptography, however, this redundancy is, ideally, deeply compromised to the point of non-existence. Highly diffuse ciphertext (that is, "secure" cryptography) becomes very "brittle" in transmission. Even a small copying or transcription error may render much or all of the resulting ciphertext impossible to decrypt. Very careful transcription, or error-correction codes (as we use today) are a practical necessity for cryptography.[57]

Modularity

For Alberti, modularity was a byproduct of the introduction of movable type. Creating manuscripts by hand required the inscription of letters *in* *situ* (at the time of production), but on a printed page, letters pre-exist as units of (literal) type before the creation of the words in which they occur. Indeed, the "mechanical regularity of print," Roy Harris argues, "confers upon each alphabetical symbol an *independence* and a constant visual identity which no earlier form of writing quite achieves."[58] This concreteness, independence, and regularity of print suggests to its users that letters are distinct from their context, which could be moved about and substituted in modular ways.

In Alberti's writing, the letter became a metaphor for modularity, suggesting that the architectural form of the ciphertext message could be assembled just as a word is created from its constitutive letters. That is, the invention of the movable type press transformed abstract letters from icons in the imagination to fungible but real materials. With the movable type press, it was clear that individual letters (in the form of literal pieces of metal) were distinct, yet produced identical marks as output. Similarly, Walter Ong argues that the invention of movable type much more strongly implied a sense of modularity than by the written alphabet alone. According to Ong, the "discrete" letterforms of the printing press were modular and interchangeable because written letters had long stood as symbols, which, with the introduction of type, became modular forms that could be manipulated. One consequence of this change was that the letter, not the page, became the locus of identity.

Cryptographic systems, such as Alberti's cipher wheel, require preexisting, modular "plaintext." Plaintext, however, could be nearly anything, so long as the appropriate translations were made. Plaintext is, therefore, the result of turning a subject into notation, which included the various ways that text would be "read off" the Book of Nature, as Bacon later explored. The kinds of "text" to emerge from reading nature were usually alphabetic, however, for example, Bacon also envisioned other marks as suitable types of plaintext. In Alberti's *Descriptio*, numerals and other kinds of notation were also considered possible plaintext marks. We might also look at John Wilkins' cryptographic and artificial language writing as well, in both *Mercury* and the *Essay towards a Real Character and Philosophical Language*, to see notations composed in line or dot form. Whether the marks were letters, numerals, lines, dots, or something else, they needed to be of a kind of mark that could be modularly replaced, because the very act of encryption, as made literally clear with the cipher wheel, was to replace one letter with another.

Indexicality

As print suggested that letters were things, letters also came to be seen as more strongly indexical.[59] Paradoxically, by making letters more concrete, it became easier to see how letters could stand in for more abstract things, which were previously difficult to combine and analyze, or as would later become critically important, to "compute."

According to Carpo, in his architectural works Alberti sought "indexical sameness," and had a "quest for identical replication."[60] However, Carpo here elides an important distinction between "indexical sameness" and "identical replication." Indexical sameness forms a kind of identity (made possible by, among other things, notational marks), whereas identical replication symbolically links objects through a visual field based on mimetic similitudes. For example, the xylographic printing press certainly did create visually identical books—identical pages neatly organized and bound together to create a unified whole. However, the key to understanding the logic of indexicality that resulted from the invention of the movable type press is to recognize that movable type utilized individual and (re)combinable letters to form new identity alliances and did not attempt to expose or extract hidden resemblances as found in mimetically associated marks. This was an important shift in the way identity formed across symbols, and it created a stronger link between the signifier and signified. In fact, given that, for encryption, identity forms in a pre-symbolic, entropic realm (as realized by Kittler's articulation of the notational epoch, discussed above), this indexical relationship is really a pre-symbolic selection of marks from a greater totality.

Whereas mimetic expression works on the level of how things do and do not look alike, notation works by dividing things into neatly-defined boxes, that is, by creating artificial identities or "tokens" of "types." These artificial identities can then be referenced by other notational marks, and so on. For encryption and decryption, the indexical reference, tying notation to notation, works without ambiguity or semantic "slack," which is why encryption can "losslessly" return to the original message through decryption. This is an important criterion for cryptography, since if any ambiguity were to be introduced during encryption or decryption, the very *idea* of cryptography would be vacated, and instead we would be dealing with guesswork, or at best, cryptanalysis.

Combination

The invention of letters and the printing press suggested a new combinatory way of thinking. That is, the novelty of printing from movable type drew attention to the combinatory logic inherent to the alphabet.[61] For natural language, the alphabet (and the associated sounds) serves as a potential storehouse for expression (constituting an evolving dictionary of permissible letter formations), which, through the agency of linguistic actors, is able to build meaningful words from meaningless parts. The movable type press, however (as I described above), enacts the modular replacement of one letter for another, which is to enact the explicit combination of letterforms. In cryptography, ciphertext draws on an even greater storehouse than language or the material letterforms of the movable type press.

The key feature of the cipher wheel is to create greater complexity than can be understood by linguistic actors, an action or performance that draws on new "alphabets" with each turn of the wheel. As each new "alphabet" is introduced, the combinatory "space" is increased, and the indexed letter references another from an ever-greater and deeper storehouse. This is precisely the reason methodological cryptanalysis of polyalphabetic encryption takes so long—the size of the storehouse is not limited to a possible dictionary or the jobbing tray of the typesetter—but instead draws on the totality of combination of the introduced alphabets.

In fact, this kind of combinatorial thinking or investigating became a practical, scientific method. One of the more famous examples comes from Leibniz, who, in his *Dissertatio,* developed a method for investigating new relationships called "*ars combinatorial*."[62] In this early work, Leibniz suggested that by combining letters and interrogating their resulting configurations, which he called "complexions," one could explore all aspects of reality, in ways quite similar to Lull's *Art* from several centuries prior. Each complexion could be organized into a table or run through a calculating mechanism (resembling cryptographic apparatuses), so as to compare identities that might reveal orders and proximate relationships.

Mimesis in an Emerging Notational Epoch

Alberti never saw his role in history so clearly. Retrospectively, Alberti's contribution looks like a form of writing and a method of analysis, which in some ways anticipated later developments in computation. Nor did many of Alberti's contemporaries and followers see their role in the development of a notational epoch very clearly either. Many cryptographers turned to mimetic techniques and theories of representation while simultaneously developing systems of notational representation.

Alberti himself used and developed mimetic theories in his descriptions of painting and the plastic arts. In *De pictura*, he claimed that the artist's goal was to create a kind of illusion so powerful that, for example, even centuries later a portrait would possess powers of resemblance sufficient to cause a viewer's heart to palpitate.[63] Similarly, the cryptographer Johannes Trithemius (1462–1516) often turned to the hidden powers of resemblances when developing his cryptographic communication systems. Trithemius developed a system of "sympathetic" pin pricks for distant communication, relying on the powers of hidden resemblance.[64] Likewise, while Trithemius' *Polygraphia* (1518) included an apparatus similar to Alberti's cipher wheel, his earlier *Steganographia* (posthumously published in 1606) recommended the use of crudely drawn images, resembling spirits, to facilitate instant and secret communication. Despite also being an accomplished cryptographer, Athanasius Kircher also believed that Egyptian hieroglyphs *visually* depicted inner truths about the world, through a hidden resemblance of the hieroglyphic symbols.[65] Or, finally, consider the ways that Bacon turned to mimetic powers. Despite the thoroughly notational nature of his "bi-literal" cipher, which analyzed the natural world in terms of binary notation, he also believed that the purity of the Chinese language, critical for his development of a "Real Character,"[66] was only possible because of an isomorphic link between their oral expression and hidden aspects of nature.

There is, in fact, no necessary reason to exclude mimetic characteristics from notational marks. Sometimes, the apparent powers of the alphabet, as they were put to work through the movable type press and cryptographic machines, were also fetishized and explored in their literal form. Such interests doubled back toward mimesis, as a kind of *typographic* mimeticism. For example, Francis Mercury van Helmont (1614–*c.* 1698–1699) thought that Hebrew letters depicted a literal homomorphism between the letterform and the speech organs. Indeed, Umberto Eco calls van Helmont's theory "a radical version of the mimological [mimetic] theory."[67] Spoken words derived from their letterform, according to van Helmont, *because* of the letter's visual similarity to speech organs in the mouth.

The movable type press, however, is just a mechanism for organizing letters on a printed page, and letters have been around for more than three millennia. By extension, Alberti's cipher wheel and its cryptographic decedents also just organize letters on the page, but in a more complex and thorough way. I argue that the historical novelty—the big invention of the movable type press and the cipher wheel—lay in the development and deployment of the notational logics, the reproducible, modular, indexical, and combinatory forms of representation.

The notational epoch, as it gained currency following Alberti's pioneering work in architecture and cryptography alike, also continued to develop. Following other cryptographers, and figures such as Leibniz and Boole, notation was increasingly operationalized and instrumentalized. By the twentieth century, the last vestiges of occult resemblances had finally been instrumentalized. Any serious study of cryptography came to accept that the field was no longer problematically mysterious.

The last moment in history when it was possible to seriously question whether cryptography operated on illusions and resemblances came to an end in the twentieth century. In 1945, Claude Shannon developed the "Mathematical Theory of Communication" that excluded, *de jure*, all hidden meanings of transmitted symbols.[68] However, Shannon's work on his purely syntactic theorems and measurements of communication were first developed during his study of cryptography during the Second World War.[69] With this last example, cryptography again had a pivotal role in the development of modern computing and information communication.

Notes

1 *De componendis cifris* was written in 1466 and remained in manuscript form during Alberti's life. A modern English translation by Kim Williams is available in Kim Williams, Lionel March, and Stephen R. Wassell, *The Mathematical Works of Leon Battista Alberti* (Basel: Springer Basel 2010). Reference will be made to this edition, using modern page numbers and section divisions. The modern Latin version has been published in Aloys Meister, *Die Geheimschrift Im Dienste Der Päpstlichen Kurie von Ihren Anfängen Bis Zum Ende Des XVI Jahrhunderts* (Paderborn: F. Schöningh, 1906).
2 Giovanni Battista Alberti, "De Componendis Cifris," in *The Mathematical Works of Leon Battista Alberti*, ed. Kim Williams, Lionel March, and Stephen R. Wassell (Basel: Springer Basel, 2010), 170. It seems Alberti was aware of Gutenberg's work as well as Arnold Pannartz and Konrad Sweinheim's (who introduced Roman typefaces); see March's commentary in Williams, March, and Wassell, *Mathematical Works*, 189.
3 Mario Carpo, *Architecture in the Age of Printing: Orality, Writing, Typography, and Printed Images in the History of Architectural Theory* (Cambridge: MIT Press, 2001).
4 Anthony Grafton, *Leon Battista Alberti: Master Builder of the Italian Renaissance* (Cambridge: Harvard University Press, 2000), 331. Williams defers to Grafton to make this point; however, Grafton never actually claims that the reference in *De cifris* was to seek sponsorship for publication. Rather, Grafton claims that Alberti's dedication to G.A. Bussi, in *De statua*, was a request for Bussi, as editorial advisor to Pannartz and Sweinheim, to seek publication of *De statua*.
5 David Kahn, *The Codebreakers: The Story of Secret Writing* (New York: Macmillan, 1967).
6 This conception of "notation" is drawn from Nelson Goodman's theory of notation, as described in his *Languages of Art* (1976). Nelson Goodman, *Languages of Art: An Approach to a Theory of Symbols* (Indianapolis, IN: Hackett Publishing, 1976).
7 In the context of mathematics, Stephen Wolfram has described this dearth of research, noting that Florian Cajori's *A History of Mathematical Notation* is one of the few histories of notation. Outside of mathematics (and to a very small degree, chemical notation), the importance of notation has not even yet been realized. Stephen Wolfram, "Mathematical Notation: Past and Future" (paper, *MathML and Math on the Web International Conference*, Urbana-Champaign, IL, 2000). Florian Cajori, *A History of Mathematical Notations* (London: The Open Court Company, 1928).
8 Friedrich Kittler, *Discourse Networks 1800/1900* (Stanford, CA: Stanford University Press, 1990), 369.
9 Ibid., xii.
10 Michel Foucault, *The Order of Things: An Archaeology of the Human Sciences* (New York: Routledge, 2002).
11 C.f., Jacques Derrida, *Of Grammatology*, trans. Gayatri Chakravorty Spivak (Baltimore, MA and London: The Johns Hopkins University Press, 1998).
12 Walter Ong, *Orality and Literacy: The Technologizing of the Word* (New York: Routledge, 2002), 22.
13 Ong offers an extensive list of the psychodynamics of expression in an oral culture; see Ibid., 36 ff.
14 Plato, *Republic*, 394c; John M. Cooper and D.S. Hutchinson, eds. *Plato, Complete Works*. Indianapolis, IN: Hackett Publishing, 1997.

15 Ibid., *Republic*, 393d, 394d.
16 Ibid., 597ff.
17 Ibid., 596e.
18 Ibid., 596d.
19 Stephen Halliwell, *Aristotle's Poetics* (London: Duckworth, 1998).
20 Ibid., 5.
21 Foucault, *Order*, 19.
22 A translation of some of Lull's work, including the *Ars Brevis* (one of his major works that was revised many times over many years), is available in Ramón Llull, *Doctor Illuminatus*. Ramón Llull, *Doctor Illuminatus: A Ramón Llull Reader,* ed. Anthony Bonner (Princeton, NJ: Princeton University Press, 1993).
23 Lull's *Art* was modelled after the Trinitarian Godhead: *intellectus*, an art of knowing and finding Truth; *voluntus*, an art of training the will towards loving Truth; and *memoria*, an art of memory for remembering Truth.
24 There are several figures to Lull's art, and they developed during his prolific career. In the *Ars Brevis* the first, second, and fourth figures are circular, while others use a tabular format.
25 Llull, *Doctor Illuminatus*, 301.
26 The historical connection between Lull and Alberti was first made by Kahn, however, he admits that there is no causal proof of the connection. He notes that the "resemblance of this device [Lull's First Figure] to Alberti's disk is striking." David Kahn, "On the Origin of Polyalphabetic Substitution," *Isis* 71, no. 1 (1980): 125.
27 Reconstruction by author, modelled after the copy of *Ars Brevis* held in the Biblioteca El Escorial, Madrid Ms. f.IV.12 folio 3r.
28 The insight of recent cryptographers to call the origin and/or result of cryptography "plaintext" is a useful distinction, as it highlights the ways that mere "text" is different from "plaintext," even if the set of marks are identical.
29 Peter Pesic, *Labyrinth: A Search for the Hidden Meaning of Science* (Cambridge: MIT Press, 2000).
30 Francis Bacon, "Translation of the 'De Augmentis,'" in *The Works of Francis Bacon*, ed. James Spedding, Roberts L. Ellis, and Douglas D. Heath (Boston,MA: Houghton, Mifflin and Company, 1900), 117.
31 Carpo, *Architecture*, 120.
32 Kahn, however, does not believe that Alberti's *Descriptio Urbis Romae* device has any historical connection to the cipher wheel (Kahn, "On the Origin of Polyalphabetic Substitution").
33 Reconstruction by Bruno Queysanne and Patrick Thépot. Image used with permission of Patrick Thépot.
34 Carpo, *Architecture*, 123.
35 Ibid., 122. Carpo notes that "the key piece of hardware in Alberti's *De statua* was a revolving instrument, a wheel of sorts, in this case somehow inconveniently nailed to the head of the body to be scanned." Mario Carpo, *The Alphabet and the Algorithm* (Cambridge: MIT Press, 2011), 55.
36 "*domicilia*" (xii) (Alberti, "De Componendis Cifris," 180). Note that, like Lull's Art, Alberti uses terminology explicitly drawn from the tradition of the memory arts, calling his indexes "houses," which are *loci* for the memory.
37 Alberti, "De Componendis Cifris," 181, xiv.
38 Ibid., 179. "Itaque aut usitate littera uti est .a. aliam quampiam significabit, ut puta .g. et littera .b." in Meister, *Die Geheimschrift*, 134.

39 Alberti, "De componendis cifris." Image licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license (Buonafalce, https://commons.wikimedia.org/wiki/File:Alberti_cipher_disk.JPG).
40 See Goodman, *Languages*, 127 ff.
41 Alberti, "De Componendis Cifris," 181.
42 The term "scrambled," in English, is a common descriptor of encryption, but it is quite misleading as it suggests a destructive operation. See Quinn DuPont, "Cracking the Agrippa Code: Creativity without Destruction," *Scholarly and Research Communication* 4, no. 13 (2013): 1–8.
43 Meister, *Die Geheimschrift,* iv.
44 Ibid., iv.
45 See Alberti, "De Componendis Cifris," 173–178.
46 Ibid., 179, xi. Della Porta also discussed the "dislocations of the natural order of letters," see Wayne Shumaker, *Renaissance Curiosa: John Dee's Conversations with Angels, Girolamo Cardano's Horoscope of Christ, Johannes Trithemius and Cryptography, George Dalgarno's University Language* (Binghamton, NY: Center for Medieval & Early Renaissance Studies, 1982), 116.
47 Carpo, *Architecture*, 29.
48 However, since ciphertext has the appearance of a meaningless jumble of letters, the chance of copying error is also quite high.
49 Alberti, "De Componendis Cifris," 180, xii.
50 Carpo, *Alphabet*.
51 These logics were also apparent in later cryptography manuals. See Katherine Ellison's analysis of John Falconer's combinatory logic, where she argues that many of these functional aspects originally inhered in the alphabet. Katherine Ellison, "'1144000727777607680000 Wayes': Early Modern Cryptography as Fashionable Reading," *Journal of the Northern Renaissance* 6 (2014): para. 27.
52 The same problem plagued Francesco di Giorgio in the fifteenth century, whose technical drawings of hoisting cranes became so corrupt that, a century later, due to the omission of key elements (such as a working block-and-tackle system), his inventions were for all practical purposes lost. It may have been the case that some errors could be "fixed" on interpretation by a master builder already familiar with the working principles, but for those truly novel designs such errors would prove ruinous. See Thomas Misa, *Leonardo to the Internet: Technology & Culture from the Renaissance to the Present* (Baltimore, MD: The Johns Hopkins University Press, 2004), 27.
53 Carpo, *Architecture*, 18; Elizabeth Eisenstein, *The Printing Press as an Agent of Change* (Cambridge: Cambridge University Press, 1980), 47.
54 Writing numerals in longhand has the advantage of linguistic redundancy. See Carpo, *Architecture*, 119.
55 Eisenstein, *Printing Press*, 53.
56 Claude Shannon, "Communication Theory of Secrecy Systems," *Bell System Technical Journal* 28, no. 4 (1949): 656–715.
57 See also Shumaker, who argues that "Copyists—and typesetters—who must toilsomely reproduce long stretches of letters that make no sense to them are peculiarly liable to error." Shumaker, *Renaissance Curiosa*, 100.
58 Roy Harris, *The Origin of Writing* (London: Duckworth, 1986), 7 (emphasis added). For a similar idea, called "decontextualization" see Mary M. Slaughter, *Universal Languages and Scientific Taxonomy in the Seventeenth Century* (Cambridge: Cambridge University Press, 2010).
59 Ibid., 116.
60 Carpo, *The Alphabet and the Algorithm*, 28.

61 See Carpo, *Architecture in the Age of Printing*, 54.
62 Gottfried Wilhelm Leibniz, *Dissertatio de Arte Combinatoria*. An English translation is available in Leibniz, "Dissertation on the Art of Combinations." Like Alberti, Leibniz was also inspired by Lull's early combinatory explorations.
63 Alberti and Rocco Sinisgalli, *Leon Battista Alberti*, 74–75.
64 Shumaker, *Renaissance Curiosa*, 108.
65 Daniel Stolzenberg, ed., *The Great Art of Knowing: The Baroque Encyclopedia of Athanasius Kircher* (Florence: Stanford University Libraries, 2001).
66 Bacon, *The Two Bookes of Sr. Francis Bacon. Of the Proficience and Aduancement of Learning, Divine and Hvmane*; Bacon, *Of the Advancement and Proficiencie of Learning*.
67 Umberto Eco, *The Search for the Perfect Language*, trans. James Fentress (Cambridge, MA: Blackwell, 1995), 83.
68 Shannon and Warren Weaver, "A Mathematical Theory of Communication." Cf. Shannon, "A Mathematical Theory of Cryptography."
69 Fred W. Ellersick, "A Conversation with Claude Shannon." *IEEE Communications Magazine* 22, no. 5 (1984): 123–126.

Works Cited

Alberti, Giovanni Battista. "De Componendis Cifris." In *The Mathematical Works of Leon Battista Alberti*, edited by Kim Williams, Lionel March, and Stephen R. Wassell, 169–187. Basel: Springer Basel, 2010.

Alberti, Leon Battista. *Leon Battista Alberti: On Painting: A New Translation and Critical Edition*. Translated by Rocco Sinisgalli. Cambridge: Cambridge University Press, 2011.

Bacon, Francis. *Of the Advancement and Proficiencie of Learning; Or, The Partitions of Sciences, Nine Books. Written in Latin by the Most Eminent, Illustrious and Famous Lord Bacon. Interpreted by Gilbert Wats*. Translated by Gilbert Wats. Golden Ball in Osier Lane. London: Thomas Wiliams, 1674.

———. *The Two Bookes of Sr. Francis Bacon. Of the Proficience and Aduancement of Learning, Divine and Hvmane*. London, Printed [by N. Okes] for W. Washington, 1629.

———. "Translation of the 'De Augmentis.'" In *The Works of Francis Bacon*, edited by James Spedding, Roberts L. Ellis, and Douglas D. Heath. Boston, MA: Houghton, Mifflin and Company, 1900.

Cajori, Florian. *A History of Mathematical Notations*. London: The Open Court Company, 1928.

Carpo, Mario. *Architecture in the Age of Printing: Orality, Writing, Typography, and Printed Images in the History of Architectural Theory*. Cambridge: MIT Press, 2001.

———. *The Alphabet and the Algorithm*. Cambridge: MIT Press, 2011.

Cooper, John M. and Douglas S. Hutchinson, eds. *Plato, Complete Works*. Indianapolis, IN: Hackett Publishing, 1997.

Derrida, Jacques. *Of Grammatology*. Translated by Gayatri Chakravorty Spivak. Corrected. Baltimore; London: The Johns Hopkins University Press, 1998.

DuPont, Quinn. "Cracking the Agrippa Code: Creativity without Destruction." *Scholarly and Research Communication* 4.13 (2013): 1–8.

Eco, Umberto. *The Search for the Perfect Language*. Translated by James Fentress. Cambridge, MA: Blackwell, 1995.

Eisenstein, Elizabeth L. *The Printing Press as an Agent of Change*. Cambridge: Cambridge University Press, 1980.

Ellersick, Fred W. "A Conversation with Claude Shannon." *IEEE Communications Magazine* 22.5 (1984): 123–126.

Ellison, Katherine. "'11440007277776076 80000 Wayes': Early Modern Cryptography as Fashionable Reading." *Journal of the Northern Renaissance* 6 (2014). www.northernrenaissance.org/1144000727777607680000-wayes-early-modern-cryptography-as-fashionable-reading/.

Foucault, Michel. *The Order of Things: An Archaeology of the Human Sciences*. New York: Routledge, 2002.

Goodman, Nelson. *Languages of Art: An Approach to a Theory of Symbols*. Indianapolis, IN: Hackett Publishing, 1976.

Grafton, Anthony. *Leon Battista Alberti: Master Builder of the Italian Renaissance*. Cambridge: Harvard University Press, 2000.

Halliwell, Stephen. *Aristotle's Poetics*. London: Duckworth, 1998.

Harris, Roy. *The Origin of Writing*. London: Duckworth, 1986.

Kahn, David. "On the Origin of Polyalphabetic Substitution." *Isis* 71.1 (1980): 122–127.

———. *The Codebreakers: The Story of Secret Writing*. New York: Macmillan, 1967.

Kittler, Friedrich. *Discourse Networks 1800/1900*. Stanford, CA: Stanford University Press, 1990.

Leibniz, Gottfried Wilhelm. *Dissertatio de Arte Combinatoria*. Leipzig: Joh. Simon Fickium et Joh. Polycarp, 1666.

———. "Dissertation on the Art of Combinations." In *Philosophical Papers and Letters*, edited by Leroy E. Loemker, 73–84. The New Synthese Historical Library 2. Dordrecht: Kluwer Academic Publishers, 1989.

Llull, Ramon. *Doctor Illuminatus: A Ramón Llull Reader*, edited by Anthony Bonner. Princeton, NJ: Princeton University Press, 1993.

Meister, Aloys. *Die Geheimschrift Im Dienste Der Päpstlichen Kurie Von Ihren Anfängen Bis Zum Ende Des XVI. Jahrhunderts*. Paderborn: F. Schöningh, 1906.

Misa, Thomas J. *Leonardo to the Internet: Technology & Culture from the Renaissance to the Present*. Johns Hopkins Studies in the History of Technology. Baltimore, MD: The Johns Hopkins University Press, 2004.

Ong, Walter J. *Orality and Literacy: The Technologizing of the Word*. New Accents. New York: Routledge, 2002.

Pesic, Peter. *Labyrinth: A Search for the Hidden Meaning of Science*. Cambridge: MIT Press, 2000.

Shannon, Claude. "A Mathematical Theory of Cryptography." Murray Hill, NJ: Bell Labs, September 1, 1945. www.cs.bell-labs.com/who/dmr/pdfs/shannoncryptshrt.pdf.

———. "Communication Theory of Secrecy Systems." *Bell System Technical Journal* 28.4 (1949): 656–715.

Shannon, Claude, and Weaver, Warren. "A Mathematical Theory of Communication." *Bell System Technical Journal* 27 (1948): 379–423.

Shumaker, Wayne. *Renaissance Curiosa: John Dee's Conversations with Angels, Girolamo Cardano's Horoscope of Christ, Johannes Trithemius and Cryptography, George Dalgarno's Universal Language*. Medieval & Renaissance Texts & Studies 8. Binghamton, NY: Center for Medieval & Early Renaissance Studies, 1982.

Slaughter, Mary M. *Universal Languages and Scientific Taxonomy in the Seventeenth Century*. Cambridge: Cambridge University Press, 2010.

Stolzenberg, Daniel, ed. *The Great Art of Knowing: The Baroque Encyclopedia of Athanasius Kircher*. Florence: Stanford University Libraries, 2001.

Williams, Kim, Lionel March, and Stephen R. Wassell, eds. *The Mathematical Works of Leon Battista Alberti*. Basel: Springer Basel, 2010.

Wolfram, Stephan. "Mathematical Notation: Past and Future." Paper presented at the *MathML and Math on the Web International Conference,* Urbana-Champaign, IL, 2000. Available online at: www.stephenwolfram.com/publications/mathematical-notation-past-future/.