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On Folding: Introduction of a New Field of Interdisciplinary Research

I.

Folding "is at work everywhere,"[1] it bends and weaves, it manifests and creates, it nourishes and is nourished, it operates materially and materializes operationally. Nature, and, one might claim, organic matter, is modulated through and impregnated by folding: one might wonder whether there is a limit to folding within and outside the organic realm of matter, since it seems to involve all scales, from the largest – as with inorganic geological folding processes – to the smallest – as with the DNA molecule.

Folding can be taken as a materialized operation: some frogs fold leaves to secure their eggs,[2] while chimpanzees fold leaves to swallow them whole.[3] Some trees fold their leaves while it rains or after certain hours.[4] As a spatial operation, folding can occur in at least three different dimensions. One-dimensional linear folding of fibers, two-dimensional planar folding of strata, leaves or surfaces, and three-dimensional folding of bodies can all be considered as various, spatial and architectural layers of matter as well as geometrical processes of folding.[5] Back to the most basic of organic levels, the protein, the brain or the embryo, as what one might call the beginning of life or its basic units, materialize operationally through and by folding and folds. Proteins fold themselves with amazing

1 Deleuze/Guattari 1984, 1: "Ça fonctionne partout, tantôt sans arrêt, tantôt discontinu."
2 For example the waxy monkey tree frog. See Wells 2007, 47.
3 Huffman et al. 2013, 20.
4 See e.g. the tree Albizia saman. See also: Satter et al. 1974, 413.
5 O'Rourke and Demaine also approach folding from the perspective of different dimensions: "The objects we consider folding are 1D linkages, 2D paper, and the 2D surfaces of polyhedra in 3-space." In: Demaine/O'Rourke 2007, xi.

speed, which begs the question: how does protein ‘know’,[6] out of million possible folds, to choose the right one so quickly?[7] The embryo and the brain materialize themselves only through the process of being folded adaptively.[8] The fold, we claim, is a material operation or/and an operative material starting at the molecular and ending at the macro level.[9]

In human culture folding plays an essential role as well. It is found in techniques of textile manufacturing, such as weaving, knotting and braiding, in calculating[10] and more importantly in cultural techniques of writing. Each technique might be thought as dealing with a sequential series of signs. Note, for example, Alexandre-Théophile Vandermonde’s 1771 system of notation for knots, arising directly from folding, weaving and the textile industry,[11] or consider the origins of computer-science as having its roots in weaving: Basile Bouchon’s 1725 punch-card controlled loom further improved on by his assistant Jean-Baptiste Falcon as a precursor to the highly successful Jacquard loom of 1805.[12] In addition, the mathematician Carl Friedrich Gauss first attempted to find a formalization the braid: a collection of folded, interweaved within each other curves formulized through sequence of letters.[13] Examining the techniques of writing, papyrus was one of the ancient mediums for linear alphanumeric systems – a rolled surface. Other methods for storing information existed before and alongside paper and papyrus, for example, clay tablets,[14] knots in threads or strings (e.g. Quipu used for administrative and calculation purposes) and hieroglyphs carved into stone.[15] But looking closely at paper and papyrus, linear writing was incorporated within and enabled by the papyrus’s two-dimensional rollable surface. Papyrus had to be unrolled for writing and reading, whereas storing and transferring was done while rolled. The rolling of papyrus produces wrinkles without creases, thus rolling and unrolling served a perfect reversible way of folding and unfolding text.

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6 Here, the following question is also called for: is protein an agent, having in its possession implicit knowledge, or should one expand the agent of the *Savoir-faire*?

7 This is known as the *Levinthal’s paradox*, a thought experiment conceived in 1968. See Levinthal 1968.

8 Susan 2007, 72: “As new cells form, the embryo is forced to conform to available space. To adapt to the confined space, the embryo folds (curves) in both transverse and longitudinal planes. Folding in the transverse plane causes the embryo to become cylindrical in shape; longitudinal folding results in the head and tail folds. Structures within the embryo (e.g., heart, intestines) also undergo folding to conform to the space available to them.” See also Marín-Padilla 2011, 11.

9 See Seppi’s contribution in this anthology concerning the logic the fold beckons towards.

10 Cf. also Krämer/Bredekamp 2003, 17, where calculation, although stemming from particular cultural techniques, is described as a “forgetting machine.”

11 See Epple 1999, 52, where Epple describes Vandermonde’s invention as follows: “The mathematization of textile pattern dealt also with the rationalization through standardization” (translated by the authors). Epple links standardization in the textile industry to the standardization of notation of pattern.

12 See Schneider 2007, esp. chapter IV (system of notation for textiles) and chapter IX, regarding punch cards.

13 Epple 1998. Cf. also Epple/Krauthausen 2010, 131f. concerning the “Papiertechniken.” See also Epple’s treatment of the mathematization of the braid (Epple 1999, chapters 6.3 and 6.4). Another origin of the mathematical study of braids began with the investigation of the simultaneous movement of a finite number of points in the complex plane (ibid, 185–192).

14 In Mesopotamia, cf. Glassner 2003.

Compared with papyrus, paper is a highly foldable material and therefore able to incorporate folding processes such as creases. With the introduction of the codex, the spatial organization of text changed from that of a continuous roll to that of a sequence of pages, which are connected through the spatial orientation of the sheet. For this reason, Immanuel Kant took the sheet of written paper as a starting point for his epistemological analysis of space and geographic orientation.[16] The written line has an orientation in space, which changes as the page is turned, rotated, bent or folded. In Kant's time, a sheet of paper could have also meant a book page, printed paper that is incorporated in the complex spatial arrangement of printed sheets.

The alphanumeric code – its writing and storage – is thus deeply linked to the material operation of folding. Taking the fold as an epistemological unit, as Gottfried Wilhelm Leibniz did, shows that it is nothing but a basic one. The fold functions neither as a basic element (the indecomposable chemical element), nor as one of the composing elements of Morse code (the line and the dot). Indeed, it does give rise to other operations and elements, but one cannot point to the manner in which this unit has originated. This is where the epistemological discourse concerning folding begins. The geometric point, defined by Euclid as the basic element among all spatial elements, is for Leibniz no longer a minimal or static object, but an operation of folding.[17] Not only is the fold already there – manifest in the protein, the brain or the embryo – it is always in-between. There is always a movement from one fold to the next, refusing a reduction to the basic units of life:

> "[e]verything moves as if the re-folds [*replis*] of matter possessed no reason in themselves. It is because the Fold is always between two folds, and because the between-two-folds seems to move about everywhere:

15 Another controversial narrative regarding the development of writing from calculation is given by Denise Schmandt-Besserat, regarding the move from three-dimensional clay tokens to their two-dimensional negative imprint on their containing envelopes. According to Schmandt-Besserat, this move occurred in order to preserve the function of the three-dimensional clay tokens, by sealing them in hollow clay spheres. Cf. Schmandt-Besserat 1992.

16 Kant 1991, 29: "In a written page, for instance, we have first to note the difference between front and back and to distinguish the top from the bottom of the writing; only then can we proceed to determine the position of the characters from right to left or conversely. Here the parts arranged upon the surface have always the same position relatively to one another, and the parts taken as a whole present always the same outlines howsoever we may tum the sheet. But in our representation of the sheet the distinction of regions is so important, and is so closely bound up with the impression which the visible object makes, that the very same writing becomes unrecognizable when seen in such a way that everything which formerly was from left to right is reversed and is viewed from right to left." See also Krauthausen's contribution regarding how folding in books subverts the notions of dimensionality and directionality.

17 This conception expressed for example in: Deleuze 1993.

Is it between inorganic bodies and organisms, between organisms and animal souls, between animal souls and reasonable souls, between bodies and souls in general?"[18]

Beyond the two folds, the materialized operation and operative matter, let us briefly examine one historical cultural narrative of folding as reflected in origami. The history of origami comprises two origins: western and eastern.[19] The origin of paper folding in Japanese tradition is rooted in ceremonial packaging. It goes as far back as the 17th century or possibly earlier. The western tradition of origami can be traced back to 16th century German baptismal certificates folded into a *double-blintz*. Folding is also evident in Albrecht Dürer's 1525 manuscript *Underweysung der Messung mit dem Zirckel und Richtscheyt*, in which he suggested tracing two-dimensional drawings of unfolded polyhedra, then cutting them out to construct the finished polyhedral. [20] However, it was Friedrich Fröbel, the German inventor of kindergarten, who contributed most to the development of folding throughout Europe and beyond during the 19th century. Interestingly, in 1814, Fröbel worked as an assistant in the mineralogical museum of the University of Berlin. He assisted in the classification of the museum's crystal collection, while taking classes from Christian Samuel Weiss on crystallography and mineralogy.[21] Maintaining that the fixed laws of nature also guide the world of infants and adults, it is therefore obvious that Fröbel's ideas already contained a geometrical mathematical kernel, to be found in the spatialization and the mathematization of folding. Indeed, starting from the second half of the 19th century, one finds several school and kindergarten instructional materials referring to folding.[22] Although Fröbel did not consider paper folding a mathematical operation, it has certainly inspired such approach, culminating in Tandalam Sundara Row's work.[23] In it, folding is presented as having a purely mathematical basis: once one builds the basic folds, other folds can be derived from the already existing system. It is equally important to note that Fröbel links two-dimensional folding of paper directly to one-dimensional folding present in weaving and braiding and also to three-dimensional arrangements of building blocks. Fröbel thus shows how these different fundamental cultural practices converge in the material and spatial operation of folding. Fröbel's *Kindergarten Gifts* demonstrate it as a geometrical exercise.

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18 Deleuze 1993, 13 (translation changed).

19 We follow the historical account presented in Hatori 2011 and in Lister 1997.

20 Dürer 1525. See also Heuer 2011. Note that during Dürer's time paper folding was not considered at all a mathematical object. However, Dürer's work directly influenced the mathematicians that followed him: Wolfgang Schmid and Augustin Hirschvogel (cf. Richter 1994, 58 – 66). This method had possibly influenced Henry Billingsley's 1570 translation of Euclid's *Elements*, adopting Dürer's diagrams and folding suggestions, and also 1613 Denis Henrion's description of the folding of platonic solids, in his *Memoires Mathematiques*.

21 Cf. Lilley 1967, 15.

22 For example: Miller/Macaulay/Stevens 1855; Martin 1893.

23 Row 1893.

The two traditions of folding – the eastern and the western – merged towards the end of the 19th century, due to the introduction of Fröbel‘s system into Japanese kindergartens concomitant with Japan's opening of its borders to the western world. During the 20th century further development took hold: a standard notational system was accepted, using the one established by Akira Yoshizawa supplemented by Randlett-Harbit. With standardization there comes the possibility for an algorithm: a specific set of instructions for carrying out a procedure, in this case, the final folded form. However, what is clear from this brief overview is that origami and folding were not always conceived as codified system, composed of basic folds, basic units; for a long time it was not even considered as such.[24]

The idea that folding should not necessarily be codified is also reflected in the growing understanding of the structure of proteins and DNA – one of 20th century's most important fields of study where folded structures emerge. Even before the discovery of the double helix, molecular biologists, Alfred Mirsky and Linus Pauling, described proteins in 1936 in terms of a folded structure.[25] Folding was tightly connected to form in matter. A fundamental association between folding in organic matter (such as in proteins) and alphanumeric code is evident already in Schrödinger's famous book *What is life?* based on a lecture he gave in 1943.

Schrödinger relates code to aperiodic crystals, and offers to think of chromosomes as coded. However, he adds that

> "[…] the term code-script is, of course, too narrow. The chromosome structures are at the same time instrumental in bringing about the development they foreshadow. They are law-code and executive power – or, to use another simile, they are architect's plan and builder's craft – in one."[26]

It is obvious that, if indeed so, folded genetic material is a very special code, compared with alphanumeric and digital codes, since it not only encodes different activities but also operates as a type of motor and designer at the same time. In this sense, the fold opens the possibility for a new form of analog coding; but not as one of several types of analog codes,[27] rather in a general sense, which reflects the relations between matter and code.

24 It is interesting to note that the axiomatization of geometry based on folding took place only in 1989 independently in Justin 1989 and Huzita 1989.

25 Mirsky/Pauling 1936.

26 Schrödinger 1944, 22.

27 Analog codification, in contrast to digital codification (as a discrete representation or symbolization of information, e.g. the Morse code or the Braille system), is a continuous representation of codified information enabled by a continuous set of values (for example, voltage signals). It employs different mathematical tools compared to those of digital codes, namelyfor example, convolution and Fourier transform.

Schrödinger's point of reference is not digital code but Morse code, when he reflects on the relationship between the number of signs and their possible combinations within the "miniature code […] of this tiny speck of material,"[28] that is, when he examines the relationship between code and matter.[29]

It seems therefore that, although folding is one of the basic processes and operations in existence, it could be regarded as encoded. Nonetheless, can one say folding is or could be coded? What are the relations between folding, folded materiality and code? Is the fold a necessary constitutive condition or just an after-effect? It is here that the question of code, especially digital code, arises as what opposes folding. Digital code is normally understood as what codifies operations and processes into an alphanumeric series of signifiers, enabling us to view operations – such as folding, but also and obviously, text – as a linear series of transmissible, discrete operations,[30] which can be repeated over and over.[31] Starting from the end of the 19th century, code was no longer perceived as what stems from a codex, but rather as what codifies and externalizes thought or meaning[32] through the codification of difference itself.[33] Transmitted alphanumeric code points towards deciphering, reading and writing as what belongs to digital one-dimensional code, as we shall see later on.[34] Digital code is ultimately denuded of any sign of materiality; it represents pure form overcoming not only materiality but also the surrounding material environment and space. Folding, we claim, represents fundamentally nothing of this sort. Might it be said that digital code, comprising distinct separable elements, represses the constitutive aspect of folding?

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28 Ibid, 61. See also: "What we wish to illustrate is simply that with the molecular picture of the gene it is no longer inconceivable that the miniature code should precisely correspond with a highly complicated and specified plan of development and should somehow contain the means to put it into operation" (ibid, 62).

29 See Kay 2000, 59–66. Examining Schrödinger's lecture, how it was conceived and historiographized. Kay claims in addition that Schrödinger did not think on information or on "one-dimensional Boolean message inscribed on a magnetic tape" (ibid, 66).

30 Cf. Kittler 2008.

31 Cf. Deleuze 2003, 114.

32 See Slater, 1888, v–xvi: the sentence "The Queen is the supreme power in the realm" is coded via sentences whose words have no relations to each other. One can detect this externalization in Shannon's Master thesis (Shannon 1938), where the simplification of electrical circuits is done via Boolean algebra, i.e., as what operates automatically. Concerning this conception of Boolean Algebra, cf. Schäffner 2007. It is crucial to note that Slater 1888 refers to code as what "ensures secrecy" (Slater's 1888 book title), hence there is a transition from the codex as known-to-all to code as barely known to two individuals: sender and receiver.

33 The codification of difference in language can be seen in Morse code in the visual difference between '–' and '•'. Compare also Deleuze 2003, Chapter 12. Deleuze indicates that the diagram, composed of "asignifying traits" being neither signifiers nor significants (ibid, 100), is replaced by digital code.

34 Here we refer to Jakobson 1971, 276–278, where the problem of understanding language is turned (in the context of Markov chains, information theory and probability) into a problem of deciphering and analyzing code with its distinctive features. Compare also Cherry/Halle/Jakobson 1953 and also Halle/Jakobson 1956, 5.

This book aims to reshape the too-well-known narrative that locates folding under the category of digital code and hence allows it to disappear.[35] We wish to not merely suggest a post-digital conception of coding, but to point towards its possible incarnation through and by folds and folding. This already requires different conceptions and possibilities of codification based on an understanding of a local notion of code.[36] We attempt to do so by proposing folding as a fundamental operation that not only preceded digital code, but has also shaped it; in this context digital code emerges as a reduced form of folding. Were it to emerge as such, a reconstitution of analog code would be feasible as well. The relationship between the continuous and the discrete would have to be reshaped.

II.

Before we embark on our program, let us (presumably) step back from the cultural sphere. Let us step back from the narrative, depicting folding in its infancy as a primitive cultural technique 'progressing' towards a codification, and consider the study of protein folding during the 1950s. Towards the end of 1956, in a symposium on information theory in biology, RNA was described by the Lithuanian microbiologist Martynas Yčas as follows: "[…] the RNA molecule can be regarded as a text, written in a four-symbol alphabet, which encodes another text, the protein, written with about twenty symbols."[37] One might therefore assume the folded structure of these molecules can be coded fairly easily, as Yčas indicated: "Since both DNA and RNA are texts written in a four symbol alphabet, it is natural to suppose that the coding problem is very simple."[38] As hopeful as his prediction was, Yčas followed with: "[r]ecent evidence indicates, however, that this is incorrect."[39]

35 For an analysis of the understanding of folded structures as what can and should be codified within biology see Kay 2000, chapter 2, where Kay describes the move from a discourse of organization and specificity to a discourse of information: "Specificity […], grounded in three-dimensional molecular structures, [interchanged to] Information […], abstracted as a one-dimensional tape, a transaction devoid of experimental measures and material linkages" (ibid, 41).

36 Concerning the locality of the code, we note that, before the Mesopotamian sexagesimal place-value system evolved into the chief method of number representation in the 19th century BC, different systems of numerals were used in various contexts (Damerow 1996, 161–162), which means that the use of code was local, i.e. context-dependent.

37 Yčas 1958, 70.

38 Ibid, 89.

39 Ibid.

Why was Yčas's conception of coded DNA doomed to fail? Indeed, one might claim the above symposium is the 'wrong' epilogue to Schrödinger's codification program, as it sought to reduce RNA to the form of digital code, instead of exploring the possibilities afforded by the aperiodicity of code. As Schrödinger saw it – suggesting the interlacing of weaving and code – compared to a repeating pattern, codification was envisioned a "masterpiece of embroidery."[40] Yčas's concluded that through reduction to codification the problem of RNA structure and function becomes "very simple". Reduction makes it easy to resolve, but then Mirsky and Pauling's folded structure of proteins does not have real implications for codification. In the midst of the rise of the information technology industry, this symposium had powerful consequences regarding the discourse of folding and codification.

It is important to note that, towards the end of his paper, Yčas offered the following solution to the above problem: "This suggests that a whole series of codes of this type may exist, all having similar general properties. At present the major difficulty is not to produce a coding principle that explains the known facts, but rather to make a choice between the many that are possible."[41] The solution is not to abandon digital code but rather to stick to it. This viewpoint was expressed in a 1965 lecture by the biologist François Jacob at the College de France, where he stated that a chemical message is written not with what is drawn, but rather with alphabet, or more precisely using a code such as Morse code.[42] This corresponds to Yčas' suggestion: either a multitude of codes or a search for a better code, eventually using "the electronic computer."[43]

Here lies the problem in the conception of digital code in the study of RNA/DNA. Greatly affected not only by the Wiener-Shanon discourse but also by the invention of the *Turing machine*, the perspective that emerged at the symposium was that computation is a linear operation.[44] Alan Turing's seminal paper, *On computable numbers*, is considered one of the breakthroughs of modern computer science.[45] The paper describes a model for every computing machine and solves in addition Hilbert's *Entscheidungsproblem*.[46]

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40 Schrödinger 1944, 5.

41 Yčas 1958, 93.

42 Jacob 1965, 22: "Heredity is determined by a chemical message inscribed along the chromosomes. The surprise is that genetic specificity is written, not with ideograms as a Chinese, but with an alphabet as in French, or rather in Morse. The meaning of the message comes from the combination of words and signs in the arrangement of words into sentences. The gene becomes a phrase of a few thousands of signs, started and terminated by a punctuation" (translation of the authors). Compare also Liu 2010, esp. chapter 2.

43 Yčas 1958, 93.

44 "There is good reason to believe that machines will actually be built which can compute any number that can be computed, and which, even more generally, can arrive at the results of any thinking which can be described by explicitly-defined operations" (Quastler 1958, 7).

45 Turing 1936.

The greatest achievements of the Turing machine is arguably not in providing the proper model for a machine, but rather in supplying a definition of computability, that is, which numbers can be computed *de facto*.

Computation was done for centuries by hand, either literally, as with the abacus, or through writing, when more complicated computations demanded it. Computational apparatuses predated the Turing machine, nevertheless Turing's idea can be thought of as replacing the writing-computing hand with a mechanical process, independent of direct human intervention. However, in this exchange, the topological surface of computation was left out, much more than the human agent.[47] The two-dimensional object, the paper, as it is embedded in a three-dimensional space, was forgotten.[48]

The writing of the Turing machine is considered to be denuded of any trace of materiality. In its description, an emphasis was placed on the recording of transitions from one state to the other and certainly not on the physical materiality of the Turing machine: "A computable sequence γ is determined by a description of a machine which computes γ."[49] Indeed, computation was reduced to machine writing, based on an axiomatic system.[50] When Turing provided an account of the workings of a computer, he stated its operations could be reduced to elementary steps: "Let us imagine the operations performed by the computer to be split up into 'simple operations' which are so elementary that it is not easy to imagine them further divided."[51] In a striking parallel to Hilbert's famous remark on geometry as an axiomatic system,[52] the relation of machine operations to their actual realization was disregarded in favor of the relations between the elementary operations. In contrast to Hilbert's approach, who still made an effort to draw two-dimensional diagrams in his famous book *Grundlagen der Geometrie*,[53] Turing based his machines, and hence, the

46 Hilbert's *Entscheidungsproblem* asks whether there is a general process for determining if a given statement *A* is provable, i.e. whether there is a machine which, supplied with *A*, will eventually say whether *A* is provable, i.e. deduced from the axioms of the logical system (cf. Ackermann/Hilbert 1928, chapter 3). Turing answered in the negative (Turing 1936, 259).

47 Cf. Deleuze 2003, 104, when replacing diagram with code "[t]he hand [of the painter] is reduced to a finger [*doigt*, in French] that presses the" digits.

48 See also Friedman/Krausse's contribution to this anthology, regarding Buckminster Fuller's critique of Euclid's ignorance of the forgotten surface.

49 Turing 1936, 239.

50 Ibid, 230: "a number is computable if its decimal can be written down by a machine."

51 Ibid, 250.

52 It is important to remember that although Hilbert's views regarding geometry in particular and mathematics in general were not mathematics as an empty formal game (a view which is exemplified in his book *Anschauliche Geometrie*, Hilbert/Cohn-Vossen 1932), he stated, on his return from Halle after hearing Hermann Wiener's lecture, his famous expression, "One should always be able to say, instead of 'points, lines, and planes', 'tables, chairs, and beer mugs'" (Blumenthal 1935, 402–3).

53 Kittler advocates this approach: "the entire foundational crisis of mathematics boiled down to the question whether numbers 'exist in the human mind', […], or 'on *paper*', as […] Hilbert was able to convince his contemporaries and posterity" (Kittler 2006, 47, our italics).

computability of code, on one-dimensional linear representation: "I assume then that the computation is carried out on one-dimensional paper, i.e. on a tape divided into squares."[54] Turing even allowed for an infinite strip of paper. One may understand this continuous infinite strip as analog code that enables the digital code written on it.[55] Nevertheless, this paper machine still does away with any sign of materiality associated with the paper strip and consequently virtualizes it.[56] This influential understanding of a computing machine as a paper machine paved the way to the understanding of codification as a linear process, dealing with the transmission of information, in a way which can be emptied not only out of materiality,[57] but also out of any form of spatiality.[58] Linearity henceforth is thought of in terms of virtual linearity; it does not assume any dimensional character, as it is not embedded anywhere – spatiality is removed.

This symbolic linearity is the basis for the linearity of code; it establishes the allegedly successful encounter between biology and information theory. At this point, the French mathematician René Thom vehemently attacked the conception that biology deals with the transmission of information and should be understood in terms of a linear code:

> "I discussed [in section 7.2] […] the abuse of the word 'information' in biology; it is to be feared that biologists have attributed an unjustified importance to the mathematical theory of information. This theory treats only an essentially technical problem: how to transmit a given message in an optimal manner from a source to a receiver by a channel of given characteristics. The biological problem is much more difficult: how to understand the message coded in a chain of four letters of DNA (the usual description of which, it seems to me, needs some improvement). […] to reduce the information to its scalar measure (evaluated in bits) is to reduce the form to [of] its topological complexity […], and to throw away almost all of its significance."[59]

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54 Turing 1936, 249.

55 Cf. Derrida 2001, 20. Remarking on his artisanal writing and paper machines, Derrida says the following: "As if that liturgy for a single hand was required, as if that figure of the human body gathered up, bent over, applying, and stretching itself toward an inked point were as necessary to the ritual of a thinking engraving as the white surface of the paper subjectile on the table as support. But I never concealed from myself the fact that, as in any ceremonial, there had to be repetition going on, and already a sort of mechanization."

56 See also Dotzler 1996, 7.

57 To borrow Derrida's expression, there is a "de-paperization" of paper, i.e., of the support (Derrida 2001, 55).

58 We follow here Sybille Krämer, who wrote: "In this respect the result of the internal states of the machine, which are held by tablets, are not states of a concrete operating apparatus, but of sign configurations: this machine does not occupy any particular place in time and space, but only on paper" (Krämer 1998, 171, our translation). Departing from Krämer, we claim one might add 'virtual' paper, that is, with Turing, paper lost its concrete reference to matter.

What are the grounds for Thom's critique? Thom did not discard of the term 'code' as such, but rather called for its re-evaluation. Thom criticized Turing's conception of code. He spoke against the view that code is a priori linearized and alphanumeric, that one may read it as if it was linear text, as did Yčas, while ignoring the fact that objects in the world have a "topological complexity."[60] In the above citation, taken from section 8.4 of *Structural Stability and Morphogenesis*, Thom refers to section 7.2, there he expands on his notion of topological complexity. Thom remarks: "the [topological] complexity of *F* [a dynamical system] is rarely defined in a way intrinsic to *F* itself." Not only does the dynamical system lack intrinsic codification, but one cannot also impose an extrinsic codification without considering the family in which the system is embedded.[61] Indeed, Thom states:

> "If, as Paul Valery said, 'II n'y a pas de géométrie sans langage,' it is no less true that there is no intelligible language without geometry, an underlying dynamic whose structurally stable states are formalized by the language."[62]

Considering the fold as what represents topological complexity, Thom does not propose to codify folding by imposing on it a single language or one-dimensional linear codification.[63] Instead, he proposes to fold code. What is necessary for digital code to emerge is geometry, or in Thom's words a "topological complexity", an underlying dynamic, which is not reducible to its "scalar measures." At best, linear code should be viewed as a reduced form of folding,

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59 Thom 1975, 157. Let us note that in the last sentence Thom uses the preposition 'to' ('à' in French), whereas we suggest a more proper proposition would be 'of'. The meaning implied by 'to' is that a reduction to "bits" enables an intrinsic reduction of topological complexity. However, as footnote 62 suggests, Thom (in Section 7.2 in Thom 1975) advocates another approach (which is implied also from using the proposition 'of').

60 A similar criticism was directed at Lily Kay's book *Who Wrote the Book of Life? A History of the Genetic Code* (Kay 2000). Against the erroneous depiction of DNA as "self-replicating," as "making" proteins and as "determining organisms," Lewontin offers that "organisms are not determined by their DNA but by an interaction of genes and the environment, modified by random cellular events" (Lewontin 2001,1264).

61 Thom 1975, 127: "The scalar measures […] should be geometrically interpreted as the topological complexity of a form. Unfortunately it is difficult, with the present state of topology, to give a precise definition of the complexity of a form. One difficulty arises in the following way: for a dynamical system parameterized by a form *F*, the complexity of *F* is rarely defined in a way intrinsic to *F* itself, for it is usually necessary to embed *F* in a continuous family *G*, and then define only the topological complexity of *F* relative to *G*." Hence, it is not that a geometrical form should be defined and reduced via its scalar measures, but rather the other way around.

62 Thom 1975, 20.

63 Thom stands against Husserl's conception, presented in Husserl 1989, that the Pythagorean theorem is identical in every language: "The Pythagorean theorem, [indeed] all of geometry, exists only once, no matter how often or even in what language it may be expressed. It is identically the same in the 'original language' of Euclid and in all 'translations'; and within each language it is again the same, no matter how many times it has been sensibly uttered, from the original expression and writing down to the innumerable oral utterances or written and other documentations." (Ibid, 160).

and not the other way around. A merger of materiality and operationality – for instance, in the form of 'virtual' paper – already informs Turing's codification of computation.

III.

Digital code is realized by means of writing, reading, inscribing, copying: simple operations – a term that appears in Turing's and Yčas's work – arranged in a virtual line (as is also the case with writing, reading and so on). As these are the terms used to describe code as a linear procedure, what should then be the terms used to discuss folding?

First and foremost, it is instructive to recall the following simple fact: folding is a spatial operation. The line that appears as a result of folding a piece of paper is a spatial *effect*, an after-effect of folding paper into a three-dimensional shape. Second, we suggest that a folded code should involve additional operations which incorporate three-dimensional folding processes that go beyond the mere sequential chain of equally-connected symbols, to include three-dimensional operations, such as bending, stretching, twisting and translating.[64] Folding, as a constitutive structure, reestablishes the materiality of code and codification in three respects. First, it suggests that codification should be communicated through physical and material effects. Second, it transcends the dichotomy of the codifying symbols, namely, that these symbols can *either* represent objects or execute actions. A folded code can do both.[65] The above series of three-dimensional operations is certainly not comprehensive. In contrast to the former list of simple operations, which presupposes a priori one-to-one correspondence between code and message, it hints at the possibility of a varying adaptive structure, which could possess a differential growth unique to the structure itself. Third, the materiality of bending, stretching or twisting does not refer to ideal operations, but rather to mechanics, to the manner in which material itself changes.[66]

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64 'Translation' here is used in the sense of moving from one place to another. Note that Hermann Wiener, who wrote a short manuscript on folded models of the platonic solids in 1893, suggested also to explore the relations between these operations and the operation of half-turn, which is based on folding (*Umwendung*). See Friedman 2016.

65 One may propose that an evident example for a folded code is Gödel's theorem: Gödel proposes to codify the arithmetical system into itself (attaching to every mathematical symbol an integer). This codification causes an operation to be executed in the now-represented structure itself: it reveals the existence of the incompleteness theorem, proving that there is a sentence, which is neither provable nor impossible to prove in this system.

66 See Guiducci/Dunlop/Fratzl's contribution in this volume.

In order to exemplify this new series of operations, let us briefly review their emergence in philosophy, mathematics and biomaterials. We should emphasize we do not endeavor to produce terms that apply analogously to each. Instead, we wish to demonstrate how folding ties together materiality, logic and the symbolic.

Etymologically the English, German and French verbs *to fold*, *falten*, and *plier* are derived through Latin from the Greek *plékein* (to plait, to weave). In Hebrew the nouns derived from the verbs 'to fold' and 'to multiply' are homophones. This suggests Thom's viewpoint regarding the interweaving of language and geometry. Instead of pointing out how deeply language and thought are folded into one another, through etymological derivatives such as 'implication', 'explication' and 'application', it is essential here to turn to Deleuze-Leibniz: (un)folding is how thought interlaces itself and interlaced within itself.[67] Codification, on the other hand, does not aim to describe the interlacing of thought, material and operation. To borrow Alexander Galloway's expression in relation to his codification of Guy Debord's 1965 *Le Jeu de la Guerre*,[68] code has the "aesthetic of the superego: it mandates optimal material behavior through the full execution of rules."[69] Besides dematerialization, digital code demands totalization, as every word comes under the same symbolic system.[70] It produces an externalization of thought. As Galloway observes, the codification of Debord's game corrects and reveals players' mistakes[71] and hence irons out, one might say, the folds in thinking. As codification is but one instance of folding, folding that would cause thought to unfold itself, to move, borrowing Heidegger's terminology, between the *Einfalt* to the *Zwiefalt*.[72]

Unfolding in mathematics appears, for example, in Thom's work as a technical term (albeit not only as such). When a function f is singular, its unfolding consists of finding a family of functions having f as a member, where almost all other members of the family are not singular at all or less singular than f.[73] This might be considered a conceptual step forward: instead of studying a single function, one examines how the enveloping family of functions unfolds the singularity. In Deleuze's terms, this would mean concentrating on the space of problems, unfolded in front of us, instead of concentrating on axiomatics.[74] It is the problem that unfolds. Its solution solves nothing, and especially does not try to establish a system

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67 Cf. Deleuze 1993, e.g. 31, 49

68 Becker-Ho/Debord 2006.

69 Galloway 2009, 148.

70 This is indeed the goal in Slater 1888: an allegedly complete dictionary of codification of all English.

71 Galloway 2009, 145.

72 Heidegger 2007.

73 See e.g. Arnold/Varchenko/Gusein-Zade 1985, 285–287. See also Ferrand/Peysson's contribution in this anthology.

74 To cite one example from Deleuze's work: Deleuze/Guattari 1987, 362ff.

of basic, irreducible units, but rather to move from "one fold to another."[75] Indeed, while unfolding a singular function, one might obtain a *bifurcation set*, that is, a whole sub-family of degenerate singular functions, of whom *f* is but one member. The interplay between unfolding a singularity and the emergence of new singularities, which in turn call for additional unfolding, gives rise to a mathematical process, along the lines of Thom's description of the genesis and morphogenesis of life, as what "permit[s] it to create successive transitional regimes."[76] Unfolding and folding consequently combine into a process without origin or end.

Differential growth in biomaterials provides the last but certainly not least example. Growth of leaves, as in kale (a variety of *Brassica oleracea*), demonstrates what happens when a leaf grows faster at the rim compared with the center. Since there is only limited space for the leaf to grow, the edge of the leaf begins to bend and fold, eventually developing a fractal form.[77] Biomaterials research aims to explain growth mechanisms in sheets where folding occurs. The purpose is not to codify every aspect of growth, but rather to deal with a process, which although codified, is always in transition. As a diachronic process of differential growth, folding changes the synchronic relations between different elements in the leaf, causing yet more folding to take place.

IV.

In this volume we present a cross-section of state-of-the-art research into the concept of folding. This collection of papers ranges from physics to architecture, from biomaterials to philosophy and art, and from literature to mathematics. Each discipline exhibits folding as a constitutive operation, which does not allow itself be reduced to a mere collection of linear codes. This can be seen in the first four papers, which deal with, what one might call, the non-material emergence of folds of thought that are nevertheless material.

Karin Krauthausen's contribution (*Literary Studies, History of Science*) suggests the manner in which the physical action of folding (of book pages, scrolls or paper) points to a conceptual crossover of the notions of dimension, direction and continuity. Following in the footsteps of Jacques Derrida and Gérard Genette, as well as analyzing the etymological, historical and cultural roots of paper folding in the context of literature studies, this paper argues that the fold conveys what linear writing had previously dissolved, namely, another praxis of nonlinear multidimensional reading.

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75 Friedman/Seppi 2015.

76 Thom 1975, 289.

77 Barbier De Reuille/Prusinkiewicz 2010, 2121. See also Guiducci/Dunlop/Fratzl's contribution in this anthology.

Angelika Seppi (*Philosophy*) follows in her paper the logic of folds of thought and thinking, which crosses, ignores and shakes the chains of classical logic. Unfolding Deleuze's thoughts, Seppi cross-references a series of thinkers: Didi-Huberman, Derrida, Leibniz and Lucretius, each of whom beckoning at the other. A non-linear web, a root system, is revealed before our eyes, an unfolded thinking, which unfolds the folds, traversing known und unknown dichotomies: matter and soul, body and cloth, 'and' and 'or'.

Claudia Blümle (*Art History*) examines the folds in the paintings of El Greco. Following hidden mathematical layers that El Greco points to, Blümle discovers that the fold does not try to constitute any space, imaginary or real, in the plane of the picture itself, but is rather occupied with subverting any linear thought. Through the folded structure of drapes and gazes, a Deleuzian vector field emerges in El Greco's painting. Blümle's careful research conveys affinities with Seppi's contribution, a research that unfolds the subversion that the fold leads to and is.

The contribution by Dominique Peysson (*Physics, Art*) and Emmanuel Ferrand (*Mathematics*) is an experiment both in materiality and in the mathematical theory of folding, showing that the fold is neither a mere metaphor nor an event in pure materiality. Performing an experiment with folded sheets of paper, they demonstrate that the fold does not act only as a metaphor but has always and already material consequences whether in literature or mathematics. Revolving around the enigmatic understanding of folds by the mathematician René Thom, their contribution hints towards Krauthausen's, regarding a folded narrative that depends on its materiality and objects linearity, and towards Seppi's regarding the Deleuzian conception of the fold.

Folded materiality points in several directions, two of which are explored in the following four papers. The first is architecture, presumably dealing with static structures. The second is physics and biomaterials research, dealing with the stable structures of matter. However, thinking through folding demonstrates these disciplines deal with nothing similar to stability or stasis.

Sandra Schramke's contribution (*Architecture*) concerns the architect Peter Eisenman, who during the 1990s invented a new architectural language with the shape of the fold. Eisenman's work is based on Gilles Deleuze's writings and René Thom's chaos theory. Eisenman understands the fold as a form that builds a bridge between an inner and an outer world, between geometry and a mental state. The fold is based on the geometry of the grid, on perception as well as mathematical theories. Furthermore, the form of the fold implements models from the natural sciences, but without compromising the singular space of perception, which honors the Deleuzian event, inevitably connected with the fold. Eisenman's reflections regarding the fold deal with American neo-pragmatism, which led postmodernism from a dead end, in order to fulfill a new autonomy and singularity of aspirations of architecture.

Joachim Krausse (*Architecture*) and Michael Friedman (*Mathematics*) examine the multifaceted figure of Buckminster Fuller. Against the classical idea of stable structures of geometry, during the early decades of the 20^{th} century, in the form of axiomatization, group theory and model theory, Fuller posits another view of material geometry, which demands its changing materiality in return. According to Fuller, geometry is not about points, lines and planes. Simply put, it is not about using discrete elements, but rather – in line with Gottfried Semper, Aaron Klug, opening seedpods and the Jitterbug dance – about continuous transformations, unfolding structures and movement: where all of these lead to a provocation of thinking, to an unfolding of it. Thought as both architectural and material provocation of movement sharpens the ideas raised in Ferrand / Peysson's contribution, concerning the fold as what arises from movement and is apparent only through it.

The contribution by Lorenzo Guiducci, John W. C. Dunlop and Peter Fratzl (*Bio-Materials Research*) describes the physical and biological transformations and processes that take place in leaves, wood, thin tissues and seedpods among others. They allude to Fuller's work, presented in Friedman / Krausse's paper, as processes that cause a never ending change in form: bending, folding, stretching and wrinkling. The folding of materials is not only an adaption of matter to a changing environment or a response to their own external codification, but is also a manifestation of thin tissues, as if the fold is already internally codified. The materials in question comprise multiple layers that interact with one another, subject to intrinsic nonlinear strains and compressions.

The final paper by Mohammad Fardin Gholami, Nikolai Severin and Jürgen P. Rabe (*Physics*) deals with folding of graphene and other carbon-based thin films. Indeed, as is already made clear in Guiducci / Dunlop / Fratzl, folding allows for the transformation of a two-dimensional material into more complex three-dimensional configurations. This paper tackles the question: how is self-folding encoded? How does one encode a continuous change?

V.

Let us attempt to summarize. Could the material operations of folding be considered a code albeit different from alphanumeric or digital codes? This is comparable to Schrödinger's thought concerning the relationship between chromosomes and code, a moment when code was introduced into biology. In this instance Schrödinger writes: "the term code-script is, of course, too narrow."[78] Folding thus helps us to rethink the classical dichotomy between continuous magnitudes and discrete elements, as already discussed in Aristotle's *Physics*: "whereas points can touch, discrete unities exist only as a series (ἐφεξῆς), since there is no in-between (μεταξὺ) of the symbolic elements."[79] Folding forces us to combine the continuous line and the discrete symbols into one and the same operation, while avoiding the conception of the digital as what withdraws from and denudes the underlying analog code. In the same way, one needs to develop a different concept of analog code, not as a transmission that varies over a continuous range with respect to sound, light or radio waves, among other mediums, but rather as a concept that emerges from the following three general characteristics of folding. These characteristics refer both to alphanumeric and digital codes as well as to the analog code, where both aspects, the digital and the analog, stem from folding as a materialized operation.

First, we argue that the totality of code – a totality present either by aspiring to discretely codify every word in the language or by conceiving any element as a part of a continuous analog code – is a conception that folding subverts.[80] Folding by its nature is local, a local adaptability. There is no infinite folding as there is no complete codification of material folded onto the material itself.[81] Folding is local, as it is adaptive to specific local conditions. An external total code, which codifies every material in the same way, ignores local conditions and adaptions that the code has to undergo. Even in the same material itself, the same structure, the same tissue, there are areas of different folded densities, whose code adapts differently.[82] In this sense, folding has an important relation to the whole. Surface tension defines the local fold and its being operational whereas changing environmental conditions generate continuous adaptions of the folding code.

Against this move towards a totality, evident both in digital as well as analog codification, we offer to formulate a conception of "minor sciences,"[83] which do not aim towards a full

78 Schrödinger 1944, 22.

79 Aristotle 1961, Book V, Chap. 3, 227a 29–31, 96 (translation changed).

80 See Blümle's contribution to this volume, where one can come to understand the fall of folds as subverting the codification of the geometrical closed space.

81 Such an imaginary scenario is presented in Borges's *Del rigor en la ciencia*.

82 Cf. section 2.2.2 in Guiducci/Dunlop/Fratzl's contribution in this anthology. During a tree's growth, cells adapt to changing conditions (weight, temperature, moisture, etc.).

83 Deleuze/Guattari 1987, 361.

uncovering of the underlying principles, but rather gestures towards the unfolding of an aggregate of problems,[84] an aggregate of local folded spaces spun together, each of which enabling a unique different codification. The codification of a growing folding leaf or an unfolded narrative[85] via differential geometry or via literary studies may intimate mutually adaptive folding codes, where their folded structures beckon to each other developing different areas of research.

Second, we claim that folding underlies a conception of materialized symbolic operations. Let us demonstrate that with two examples, already presented in brief: 1) looking at the holes of punch cards, one may observe that, though stemming from weaving, the holes exist now as a collection of discrete objects, not only detached from any act of weaving – from the action that suggested them – but also from any reference to reading. 2) Examining a folded line, created from folding a finite piece of paper, one may now neglect the paper and regard the line as the basic element – together with the infinite planes it may span – assuming an axiomatic approach, extended to infinity.

Against the background of the above two examples, let us take our cue from the architect Gottfried Semper, who claimed that the true manifestations of walls, that is, of space enclosures and separating planes, are woven materials: braids, mats, hangings and tapestries.[86] In light of this, we aim to bring back materiality into discrete elements – the point, the line, the plane – that is to say, we wish to relate back again the act of weaving and the point, or, more explicitly, the continuous and the discrete. Weaving itself is a synthesis of discrete elements – from the holes in the punch card to the creased points of the thread while being weaved – and continuous movement – the movement of the whole loom. We aim to bring back folded materiality as what opens up possibilities for an interplay of the continuous and the discrete: a hole is made possible by the continuous movement of thread, analog code is made possible through the digital discrete encoding of the knot, the thread or the molecule, through the discrete perforation of a punch card.

Third, we would like to point out that folding underlies not an externalization of thought but rather an internalization of a three-dimensional structure, a "topological complexity" that should not be lost or forgotten via any sort of codification. *Isomers* – molecules having the same chemical formula but different chemical properties – are the simplest example in this respect. Ever since Antoine Lavoisier (1743–1794), it was common to identify a material with its chemical composition. However, in 1828, Friedrich Wöhler discovered this is not enough, when he produced urea, which has the same chemical composition as ammonium cyanate (CH_4N_2O) albeit different properties. Jacob Berzelius coined the term 'isomer' several

84 Ibid, 362.
85 Cf. Krauthausen's contribution to this volume.
86 See e.g. Semper 1983, 21.

years later. This has led slowly to the understanding that "molecules had to be understood from the perspective of stereochemistry, that is, how atoms in a molecule are arranged in space relative to one another."[87] In 1848, Louis Pasteur discovered molecular chirality by investigating tartaric acid, thereby further emphasizing the importance of topological structure.[88] What both discoveries – Wöhler's and Pasteur's – indicate is the performative character – both executing and realizing – of a folded structure in comparison with a coded one. Hence, a discrete code – as in Lavoisier's codification of chemical elements in the shape of an alphanumeric code – is problematic. Although Lavoisier developed a material symbolic code, it nevertheless could not represent materiality adequately. The linear or diagrammatic symbolic representation had to be amplified by three-dimensional elements. Wöhler and Pasteur took on this crucial step, and this insight was later also prominent in 1874 van 't Hoff's discoveries.[89] In this respect, Lavoisier's codification may be considered an extreme reduction of folded code, achieved by ignoring its materiality and spatiality.

The change imposed on Lavoisier's codification, necessitated by new discoveries, as well as other aspects of folded code/coded fold, point towards a conception of an adaptive code. More than a local, symbolic and changing digital code, where a codifying letter has already several possible ways of execution, we seek an adaptive coded material, responsive to the feedback loop (from changing environmental conditions back to the material and vice versa), which is always operative, always changing the inner codification of the material and causes folds to emerge.

On this basis we suggest digital code be regarded an instance of a broader folded interlacing between analog and digital code. Thus, the conception of digital code could be revised. As with the Turing machine, the sequence of discrete symbolic states is only made possible via the continuous, local, material band, unrolled as an old papyrus, rendering the symbols readable, executable and realizable. Folding, as a material basis for symbolic operations, thus regains its importance as an amalgamation of analog operations and discrete symbols. It alters in addition the classical idea of digital code as a dematerializing process of a purely symbolic machine. When the folded band is viewed in terms of continuous algorithms and sequential operations that control their own execution, the old notion of analog code is rehabilitated.

87 Soledad 2008, 1201.

88 Pasteur 1848. Cf. Also Caillois 1973, 55, where the discovery is described in terms of the topological complexity ("La composition chimique des cristaux est identique, mais non leur topologie").

89 van 't Hoff 1877.

This points towards future challenges to come. If folding is "at work" everywhere, and folding can be regarded as an operation, coded in material and materialized in code, then a new analysis of folding is inaugurated. Folding of fibers and threads produces series of point-like folds, whereas the folding of plane surfaces results in lines, and folding of bodies in planes. Thus, the always-becoming structures of folding combine zero-, one-, two- and three-dimensional elements, as parts of an analog code that has to be developed in a broader sense. The idea of folding, as both opening up and necessitating new conceptions of an adaptive code, requires a program for developing new horizons for analog codes. Practical consequences of future perspectives on folding would follow the following three approaches: 1) an analytical approach applied to the development of the notion of folding as an analog code in mathematics, computer science, philosophy and media theory, 2) a historical and genealogical approach to analog code,[90] 3) an experimental approach within material sciences, biology and physics. Taking into account the dualism of matter and code would open up the analysis, history and experimentation of folding as a new field of interdisciplinary research.

90 Schäffner 2016.

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