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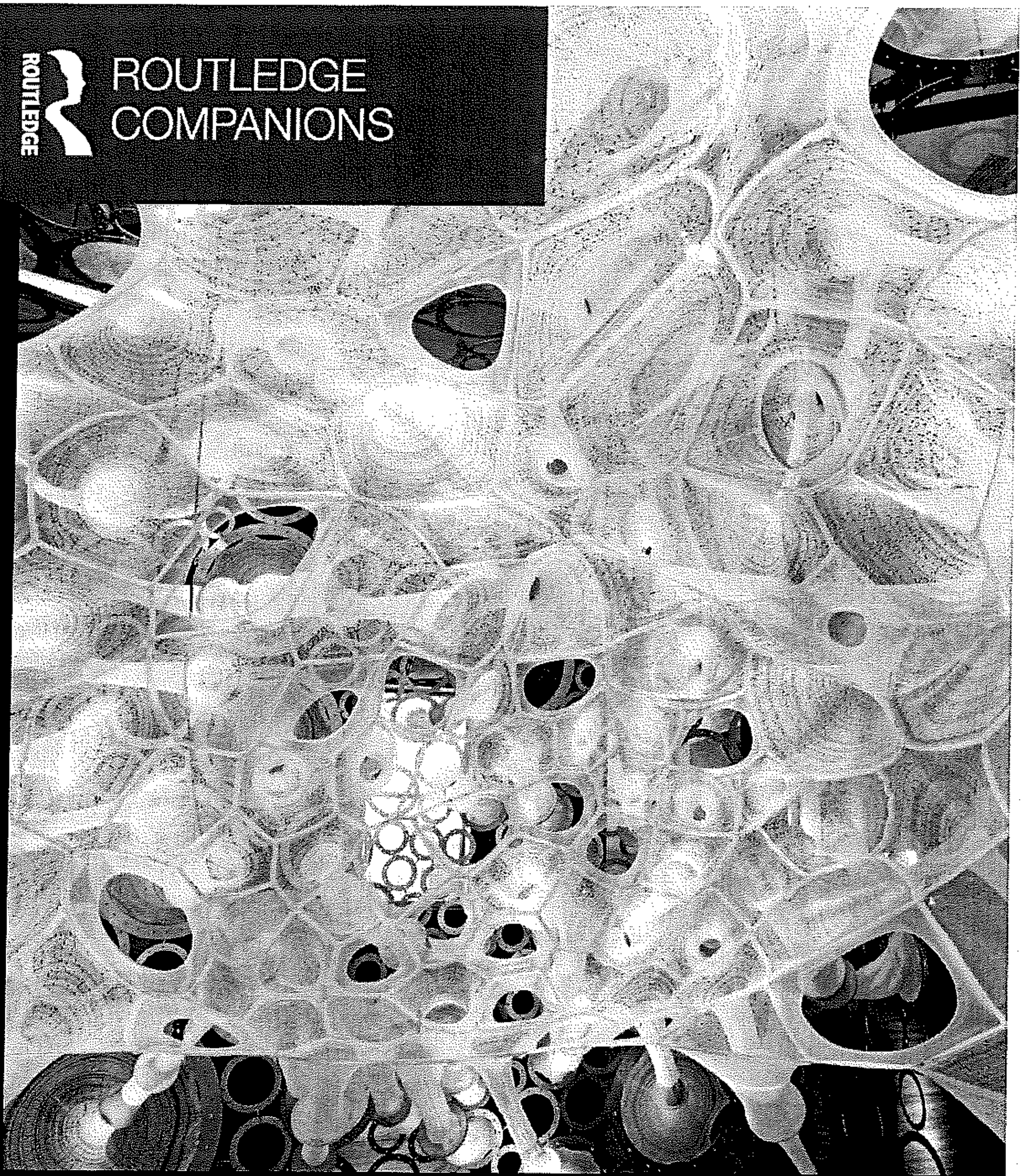

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11

Morphogenesis and Design

Thinking through Analogs

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Introduction

Digital practices in design, together with computer-assisted manufacturing (CAM), have inspired the reflection of philosophers, theorists, and historians over the last decades. Gilles Deleuze's *The Fold: Leibniz and the Baroque* (1988) presents one of the first and most successful concepts created to think about these new design and manufacturing practices.[1] Deleuze proposed a new concept of the technological object, which was inspired by Bernard Cache's digital design practices and computer-assisted manufacturing. Deleuze compared Cache's practices to Leibniz's differential calculus-based notion of the parametric curve. From this perspective, the object is no longer an essential form: rather, it is functional, defined by a family of parametric curves. In Deleuze's terms, it is an *objectile*. This definition grasps a particular aspect of modernity in the technological object, rendering possible the industrial production of "the unique object" (*la pièce unique*), while making obsolete the homogeneity that comes with industrial standardization. What follows introduces developmental biology into this design matrix, interrogating the relationship between parametric design and computer-assisted manufactory on the one hand and biological morphogenetic processes on the other. Is one necessary for the other? Does an architect need computation in order to render morphogenetic shapes? In answering these questions, this chapter displaces the centrality of digital technology in the design of shape-shifting forms within architecture and calls for a rethinking of design by way of analog prototypes. I argue that "thinking through analogs" offers another means of generating parametrically based morphogenetic forms.

In *The Alphabet and the Algorithm* (2011), the historian of architecture Mario Carpo addresses the digital within the history of architecture. In particular, he observes how new organicist and morphogenetic theories converged with mathematical theories at the end of the 1990s, in the early years of digital design within architecture. In this era, architects such as Greg Lynn, Ben van Berkel, Future Systems, Frank Gehry, and NOX/Lars Spuybroek executed an architecture of amorphous and "blobby" biological shapes. Thanks to the convergence of the biological and algorithmic, organicist and morphogenetic theories became central to digital design practices.[2] On one hand, organicist and morphological theories have been inspired by the possibilities of different phenotypes from a single genotype. On the other, digital design is based on the study of the variation of a parametric function, generating often algorithmically different, albeit similar curves from a single notation. It is easy to understand that in the domain of morphogenetic architecture the genetic terminology refers to computation: the algorithms of software make up the "genotype," while the architectural shapes produced by the algorithms constitute the "phenotypes." Carpo observes that "the analogy between generative digital scripts and DNA-like developments of form is self-evident".[3] For example, the architect Achim Menges uses the metaphor of the passage from genotype to phenotype to qualify computational morphogenesis.[4] While the scientific literature on digital morphogenesis supports Carpo's thinking, he also remarks that the analogy between generative digital scripts and DNA-like developments of form is purely metaphorical, since "the mechanic and the organic still belong, for most practical purposes, to different kingdoms of nature."[5]

This chapter historically foregrounds contemporary biologically inspired architecture—what is otherwise known as morphogenetic design—in the theories of morphogenesis developed by Alan Turing, Conrad Hal Waddington, and René Thom. I focus on the role their thinking plays in the understanding of the passage from genotype to phenotype in the development of an organism, and how this can be translated into architectural design practices. The present chapter sheds light in particular on the respective roles of genes and mathematics in their theories. I argue that for Turing, Waddington, and Thom, generative principles are not to be confused with a purely genetics-based thinking, and that by connection mathematical thinking, through the study of instabilities and symmetry breakings, plays an important role in the understanding of the genesis of forms. The chapter is divided into four sections. After the introduction, the second section focuses on the role of mathematics and physics for the study of morphogenesis in the work of D'Arcy Wentworth Thompson and Alan Turing. The third section addresses the relationship between morphogenesis and design through an interpretation of the "epigenetic landscape," introduced by embryologist Conrad Hal Waddington, who was also influenced by Thompson. I conclude in the fourth section with Turing's work on morphogenesis, in particular his ideas concerning the use and the meaning of mathematical models and of digital calculus for the study of morphogenesis in relation to real organisms.

The Subtle Relationships between Morphogenesis and Design

The age-old polemic within biology about the "argument from design" has interesting resonances in architecture. According to biographer Andrew Hodges, Alan Turing's work on morphogenesis aimed at defeating this teleological argument: the idea that, in front of the astonishing organization of living organisms, one has to postulate "argument from design," or the creation of form based on the existence of a designer.[6] Turing did not write explicitly about his anti-design position, leaving it open to interpretation. It is plausible to think, following the mathematician and theoretical biologist Peter Saunders, that Turing was in agreement with the naturalist D'Arcy Wentworth Thompson, also struggling with the argument from design.[7] The original intention of the argument from design was to provide scientific proof of the existence of God. The theistic roots of the argument from design materialized early on in the metaphor of the watchmaker imagined by clergyman and philosopher William Paley (1743–1805). Saunders recounts Paley's idea:

> If, wrote Paley, we were to find a stone on the ground, we would hardly trouble to ask how it came to be there. Suppose, however, that we were to find a watch, composed as it is of a large number of parts, each of which is formed and adjusted so that it combines with the others to keep accurate time. Surely we would be bound to infer that the watch must have

> had a maker. Similarly, so the argument runs, how can anyone look at an organism and not be forced to the conclusion that there must be an intelligent creator who designed it?[8]

The Darwinian theory of evolution refuted the argument from design, at least in the biological realm, explaining the seamless functionalism of organisms according to natural selection. Thus, one might query what drove Thompson and Turing to still feel the need to defeat the argument from design. Saunders explains that in the strict neo-Darwinian interpretation, a new version of the argument from design paradoxically returns, where natural selection acting on random, and only random, mutations plays the role of God.[9] This idea instantiates the modern evolutionary synthesis, or what Julian Huxley named the "Modern Synthesis": the fusion of population and Mendelian genetics and natural selection which gave rise to a reductionist gene-based understanding of evolution. Working through the ideas of the Modern Synthesis, Huxley wrote of Darwinism at the end of the nineteenth century:

> Darwinism grew more and more theoretical. The paper demonstration that such and such a character was or might be adaptive was regarded by many writers as sufficient proof that it must owe its existence to Natural Selection. Evolutionary studies became more and more merely case-books of real or supposed adaptations. Late nineteenth-century Darwinism came to resemble the early nineteenth-century school of Natural Theology. Paley *redivivus*, one might say, but philosophically upside down, with Natural Selection instead of a Divine Artificer as the Deus *ex machina*.[10]

Huxley's reference to Paley indicates how, in the development of the Darwinian theory, natural selection paradoxically took the role that God occupied in Paley's theory, i.e. the role of a designer.

Yet, this position seems almost unavoidable for those advocating a strong neo-Darwinian position, such as Richard Dawkins, who famously called natural selection a "blind watchmaker."[11] Dawkins, however, underscored that the action at work within an organism is, contrary to Paley's watchmaker, completely free of teleology, since it acts blindly, without intention—and randomly according to natural selection. For Dawkins, the workings of genetic expression are hardbound, if not mechanistically attached to nature. Nonetheless, Dawkins' conception of design still shares something essential with Paley's thinking: the idea that the design of something is solely a matter of its originating conception. In this rubric, there is no consideration of the process of material-making that follows.[12] Anthropologist Tim Ingold writes:

> And when a scientist like Dawkins claims that such a design is coded into the animal's DNA, whence it controls its behavior just as already wired in electronic guide to missile, he is advancing an argument from design just as strong as any to be found in Paley's natural theology.... The attribution of ultimate responsibility for the design to natural selection rather than to God does not in the least affect the logic of the argument, namely that there can no be functional complexity without prior design.[13]

These quite recent considerations about the origins of design resonate with the morphogenetic perspective in theoretical biology defended by Thompson and Turing. In fact, Thompson's perspective, further developed by Turing, goes against the idea that the genesis of forms is based on a priori design, instead opting for an idea that morphogenetic processes are material, and physical. Thompson and Turing criticized the rigid interpretation of Darwinism—neo-Darwinism—which allowed for little scientific inquiry into the origin of the different forms. Thinking about the generation of forms by contrast from the morphogenetic perspective, Thompson and Turing prioritized the process of the growth and development of generic natural forms, which, by connection, made central the study of the mathematical and physico-chemical generative principles at the origin of existing forms.

Following this reasoning in his seminal book *On Growth and Form* (1917), Thompson argued that the role played by mechanics and physics had heretofore been underestimated in the study of morphogenesis. Without abandoning Darwinism, Thompson maintained that factors other than natural selection come into play in the genesis of natural forms. Thompson cited, for example, the structural transformations determined by forces:

> Cell and tissue, shell and bone, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, moulded and conformed.... Their problems of form are in the first instance mathematical problems, their problems of growth are essentially physical problems, and the morphologist is, *ipso facto*, a student of physical science.[14]

Similarly, Turing wrote in his late work on morphogenesis from 1952 that "the theory [of morphogenesis] does not make any new hypothesis; it merely suggests that certain well-known physical laws are sufficient to account for many of the facts."[15] Here, the logic in the study of morphogenesis is not based on robust selection rooted in functional adaptation, which is arguably another way of describing the "argument from design," but rather a means to get at the role of naturally generated forms, i.e. forms that emerge from Thompson's take on force.

Epigenetic Landscapes as Dynamical Systems

Returning below to Turing's work on morphogenesis and its relationship to digital calculus, here I address the following question: how can one use an understanding of morphogenesis for design purposes, bypassing the above-mentioned tension between morphogenesis and design? Based on the work and writing of architects and designers on digital morphogenesis, one possible way to get at this question is through architectural praxis in the field. However, what follows relates an experience of non-computationally based morphogenetic design within the framework of a school of applied art, the, École Nationale Supérieure des Arts Décoratifs (ENSAD) in Paris. First I introduce embryologist Conrad Waddington's "epigenetic landscape," and then discuss my implementation of his ideas with students at a design studio at ENSAD. No calculations were used in this studio to conceive forms. We developed in class a research program on morphogenesis working with analogs: our work was based on the hypothesis that, if analogic and computational approaches share the same generative principles, one can experiment with morphogenetic design without the use of computation. Instead, one manipulates the immanent properties of materials through analog techniques. Thus there are neither calculations nor subsequent 3D printing in our approach. Instead, we experimented directly with the plasticity of employed material, such as tensed membranes and ferrofluids. This process was inspired by a structural, albeit dynamical, interpretation of the image of the landscape in theoretical biology. Eliding theoretical biology into the design of architectural or artistic forms, we used Waddington's image of the "epigenetic landscape" as an inspiration to create morphogenetically based design. The epigenetic landscape is a set of mind's-eye views into the process of cellular differentiation in embryological development. Waddington first introduced this idea, even if not the expression "epigenetic landscape," in his book, *Introduction to Modern Genetics* (1939). The first image representing the epigenetic landscape and the first use of this expression appeared in the frontispiece to Waddington's *Organisers and Genes* (1940).[16] Waddington, like Turing, was inspired by Thompson's ideas about morphogenesis, mathematics, and physical forces. Furthermore, Waddington's work influenced the work of Turing on morphogenesis. In fact, Waddington's *Organisers and Genes* is among the three references from biology in Turing's "The Chemical Basis of Morphogenesis" (1952).[17]

The image of the epigenetic landscape appearing in Waddington's *The Strategy of the Genes* (1957) depicts a ball at the top of an undulating surface, on the point of rolling down a hill.[18] The ball may take any of several possible paths opened before it. This image is completed by a "hidden" part, underlying the undulating surface: a network of pegs fixed to the ground, interconnected in a redundant way by guy-ropes and strings. Some of the guy-ropes and strings are connected to the bottom of the surface. The undulating surface is a result of the emergent effects of this complex set of relationships. Waddington himself qualifies the epigenetic landscape as a mental picture that aids in understanding the process of embryological development:

> Although the epigenetic landscape only provides a rough and ready picture of the developing embryo, and cannot be interpreted rigorously, it has certain merits for those who, like myself, find it comforting to have some mental picture, however vague, for what they are trying to think about.[19]

From a performative point of view, the composite image registers the changes in the tension of connections provoked by a variety of factors, such as external perturbations and the modification of tension between two or more pegs. It is easy to imagine that these shifts may modify the form of the undulating surface, thus creating a new path, a new possibility for the ball to take. At the same time, one can imagine that some tension modifications could be balanced by other modifying tensions, so as to leave unchanged the greater play of tension of the undulating surface. This would imply that the paths offered by the undulations would not change, despite the underlying local modifications. And this could be seen as the guarantee of a certain form of robustness for the dynamics of the balls.

For Waddington, the undulating surface represents the fertilized egg. The path followed by the ball represents the developmental history of a particular part of the egg. As for the underlying part, the epigenetic landscape turns out to be a composite metaphor, offering an interpretation of the constitution of the surface itself. Waddington explains the complex system of interaction underlying the epigenetic landscape:

> The pegs in the ground of the figure represent genes; the strings leading from them the chemical tendencies which the genes produce. The modeling of the epigenetic landscape ... is controlled by the pull of these numerous guy-ropes which are ultimately anchored to the genes.[20]

The images reveal key elements of Waddington's vision of embryology. First, there is his idea of "canalization," based on the idea that development of the embryo is "canalized" along defined pathways. Second, there is the complexity of the passage from genotype to phenotype. The undulating surface on which pathways, or channels, are defined is molded by the underlying network of genetic interaction. Waddington makes explicit that his position is complex and non-reductionist, especially vis-à-vis the reductive concept of single gene action, which is the theory that one gene gives rise to one phenotypic expression. He states, "It is not necessary, in fact, to await a full understanding of the chemistry of single genes before trying to form some theoretical picture of how gene-systems produce integrated patterns of developmental change."[21] Waddington further compares the genetic actions on the whole to the geological structure molding the valleys of the landscape: beyond the field of embryo development, these images bear the structural and morphological nature of Waddington's thinking. The landscape can be thus seen as a mental picture offering a theoretical view on morphogenesis and morphodynamics in systems composed of interacting agents evolving in an environment. For that reason Waddington's images of the epigenetic landscape can be so stimulating for the design of processes in architecture and other creative fields.

Waddington sought to shore up his theories of developmental process with math. Even if he did not develop a suitable mathematical theory, he indicated dynamical non-linear systems, topology, and analysis in phase-space as fields to be explored. He knew the importance of these branches of mathematics for the development of other fields of theoretical biology, such as epidemiology, population dynamics, and the emergent sphere of cybernetics.[22] This is not to argue that the mathematical perspective is the only source of Waddington's images. We know, in fact, that these images fit well with Waddington's concerns in experimental embryology and with his experimental results on induction and competence as well.[23] However, the images defining the epigenetic landscape are not only a way to graphically express the conceptual results of Waddington's work in experimental embryology. I defend the idea that in addition to expressing experimental results, these images show a disposition to mathematical thinking. There is a morphological analogy between the undulating surface of the epigenetic landscape and the potential energy surfaces studied in statistical physics of complex systems and in systems biology.[24] Furthermore, Saunders and the developmental biologist Jonathan Slack interpret Waddington's images from a dynamical systems point of view.[25] The mathematician René Thom first advanced this interpretation in the 1960s, developing his catastrophe theory, a theory of morphogenesis based on topology and differential analysis. Thom defined catastrophe theory as a general mathematical theory of morphogenesis, describing the creation or destruction of forms, without regard for the substrate, or the nature of the determining forces. Thom himself recognized that images from embryology, and in particular Waddington's epigenetic landscape, have been both a source of inspiration and a target for the development of catastrophe theory. Thom first published his thinking on catastrophe theory in an anthology edited by Waddington, *Towards a Theoretical Biology I* (1968).[26]

The article triggered a rich and lively correspondence between Waddington and Thom about the mathematization of the epigenetic landscape in terms of dynamical systems theory. Details of the correspondence reveal some misunderstandings both of the theoretical notions associated with the landscape and the mathematical notions that might describe them. The principal disagreement coalesced around whether "homeorhesis," Waddington's neologism which indicated a state of dynamic equilibrium within the developing embryo, could be expressed in terms of the mathematical notion of structural stability.[27] This terminological misunderstanding can be interpreted from at least two perspectives. The first arises from the fact that they came from different scientific and epistemological cultures, and they did not share the same mathematical knowledges and exigencies in mathematical rigor. The second lies in the recognition of the existence of a theoretical problem, immanent in the composite image of the epigenetic landscape, which cannot be fully explained by Thom's catastrophe theory. The epigenetic landscape implicitly indicates different timescales that should be taken into account: one slow, the timescale of evolution, and one fast, the timescale of development. It is not surprising that Waddington stressed the differences between Thom and himself concerning the appreciation of the variable "time." These misunderstandings are promising in that they open a space to see Waddington's landscape in terms of mathematization. These productive misunderstandings are part of the history of attempts to understand physical and biological processes as dynamical systems.

The last letters from the Thom–Waddington correspondence reveal that Thom asked th physicist Froissart to build a model of the epigenetic landscape in clay. After a long corre spondence composed of many pages of discussion about the meaning of the theoretical tern introduced by Waddington (chreods, homeorhesis, and canalization) and the meaning of th mathematical terms Thom mobilized to describe them mathematically (attractors, structural st bility, local state, and kinetics tangent to a point), the last letters remarkably show Thom's need think through material *analog* models. This suggests that Thom needed to return to materiality order to better express his ideas. Waddington's answer also alludes to a material model of the ep genetic landscape made by Waddington himself. I quote the letters at length in order to unde score the importance of analog models—drawings and material three-dimensional models— the understanding of the dynamics of the epigenetic landscape. First, let us consider a lengt extract from a letter written by Thom to Waddington:

> Dear Wadd.,
>
> As I wrote you in a previous letter, I got the idea that your model of "epigenetic lan scape" might be somewhat improved as follows: the whole phenotypic structure of animal can be described as a potential well; let Z be the potential function, geometrical realised by the "cote", the height (vertical coordinate). Inside the potential well, there is geography describing the whole story of development: the point of lower value (absolu minimum Z) is the "germinal" point. To this point arrive three valleys, describing the ma embryological differentiations: ectoderm, mesoderm, endoderm; above, there are betwee valleys saddle points, and isolated lakes describing the formation of organs: the neural lak communicating with the ectoderm valley, the "digestive tube," at the source of the endo derm valley … and so on …. Now the main idea is that development has to be looke upon as the flooding of this landscape, conversely, gametogeneis is the "drying up" of th landscape; we let water pour into the potential well, and the shore of the lake so obtaine describes—approximately—the evolution of the embryo. (More precisely, at time T, whe the height of the water is z(t), then the embryo is represented by the level variety z = z(t) Now, for the last organ, we may take the gonad, by a very highly located lake on the slop for the mesoderm valley. To get a more complete picture of reproduction and developmen we may have two exemplars of the potential well—in plaster, or clay for instance—and w may have a small pit at the bottom of the gonad links pouring water into the second poten tial well, located below. A friend of mine, Mr Froissart, a physicist from Saclay, did realiz these two models in plaster, and they work very demonstratively, when pouring water in th top well. I feel sure that you would be interested to see this realization—despite its obviou oversimplifications.[28]

Thom describes the phenotypic structure of an organism as a potential well containing sev eral local minima of energy.[29] This is represented by the different concavities inside the plaste model. The development of the organism is seen as the flooding of this composite potentia well. The plaster model also allows Thom to represent the gametogenesis, that is the develop ment in the gonads of mature sex cells (the gametes). Gametogenesis is seen as the drying up o one of the concavities of the plaster model (concavity that represents the gonad). To realize thi desiccation it is sufficient to insert a pit into the concavity representing the gonad in the plaste model, thus the water can flow outside the gonad. Through this model Thom further recast reproduction and development according to the flow of water from a pit situated into the gona of the first potential well to a second potential well situated below the first one. This is illustrate in Figure 11.2.[30]

The last letters from the Thom–Waddington correspondence reveal that Thom asked the physicist Froissart to build a model of the epigenetic landscape in clay. After a long correspondence composed of many pages of discussion about the meaning of the theoretical terms introduced by Waddington (chreods, homeorhesis, and canalization) and the meaning of the mathematical terms Thom mobilized to describe them mathematically (attractors, structural stability, local state, and kinetics tangent to a point), the last letters remarkably show Thom's need to think through material *analog* models. This suggests that Thom needed to return to materiality in order to better express his ideas. Waddington's answer also alludes to a material model of the epigenetic landscape made by Waddington himself. I quote the letters at length in order to underscore the importance of analog models—drawings and material three-dimensional models—to the understanding of the dynamics of the epigenetic landscape. First, let us consider a lengthy extract from a letter written by Thom to Waddington:

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Bures, December 11 1967

Dear Wadd.

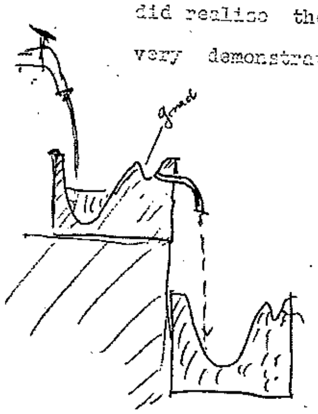
As I wrote you in a previous letter, I got the idea that your model of "epigenetic landscape" might be somewhat improved as follows : the whole phenotypic structure of an animal can be described as a potential well ; let z be the potential function, geometrically realised by the "cote", the height (vertical coordinate). Inside the potential well, there is a geography describing the whole story of development : the point of lower value (absolute minimum) is the "germinal" point. To this point arrive three valleys, describing the main embryological differentiations : ectoderm, mesoderm, endoderm ; above, there are between valleys saddle points, and isolated lakes describing the formation of organs : the neural lake, communicating with the ectoderm valley, the "digestive tube", at the source of the endoderm valley ..and so on .. Now the main idea is that development has to be looked upon as the flooding of this landscape (x) ; we let water pour into the potential well, and the shore of the lake so obtained describes -approximatively- the evolution of the embryo. (More precisely, at time t, where the height of the water is z(t), then the embryo is represented by the level variety z = z(t)). Now, for the last organ, we may take the gonad, realised by a very highly located lake on the slope of the mesoderm valley. To get a more complete picture of reproduc-

Figure 11.1 Letter from Thom to Waddington, December 11, 1967 (*continued overleaf*)

Source: Waddington Archive, University of Edinburgh.

Waddington replied to Thom also using the language of physical models to give shape to the epigenetic landscape, this time in terms of balls running along valleys, controlled in their pathways by chemical switches. An excerpt from a letter to Thom from Waddington elucidates this point:

-tion and development ,we may have two exemplars of the poten- -tial well -in plaster ,or clay for instance - ,and we may have a small pipe at the bottom of the gonad lake pouring water into the second potential well , located below .
A friend of mine , Mr Froissart , a physicist from Saclay , did realise these two models in plaster , and they work very demonstratively ,when pouring water in the top well .



I feel sure that you would be interested to see this realization -despite its obvious oversimplifications . If you don't have an opportunity to come to Paris before , I certainly shall bring these models to Bellaggio next summer .(If the meeting is going to take place).

The M.S. of my book after several additions - notably concerning language and grammatical functions - is now by the editor . But because of several difficulties with the illustra- -tions , it won't get printed before next Spring . As soon as I have proofs , I shall send them to you .

Very sincerely yours

René Thom

RThom.

P.S. Thank you for the material from Bellaggio II.

(x) Conversely ; gametogenesis is the "drying up" of the landscape.

Figure 11.1 (*continued*)

Thanks very much for your letter describing your model of an epigenetic landscape in the form of a potential well which can be flooded. I am sure you can express the ideas very well in this form and I shall look forward to see it. I have myself, in the past, made one or two physical models of the epigenetics landscape in which balls ran along valleys etc. with switches to control the way they went. I shall see if I can find one of them, or at any rate a photograph of it.[31]

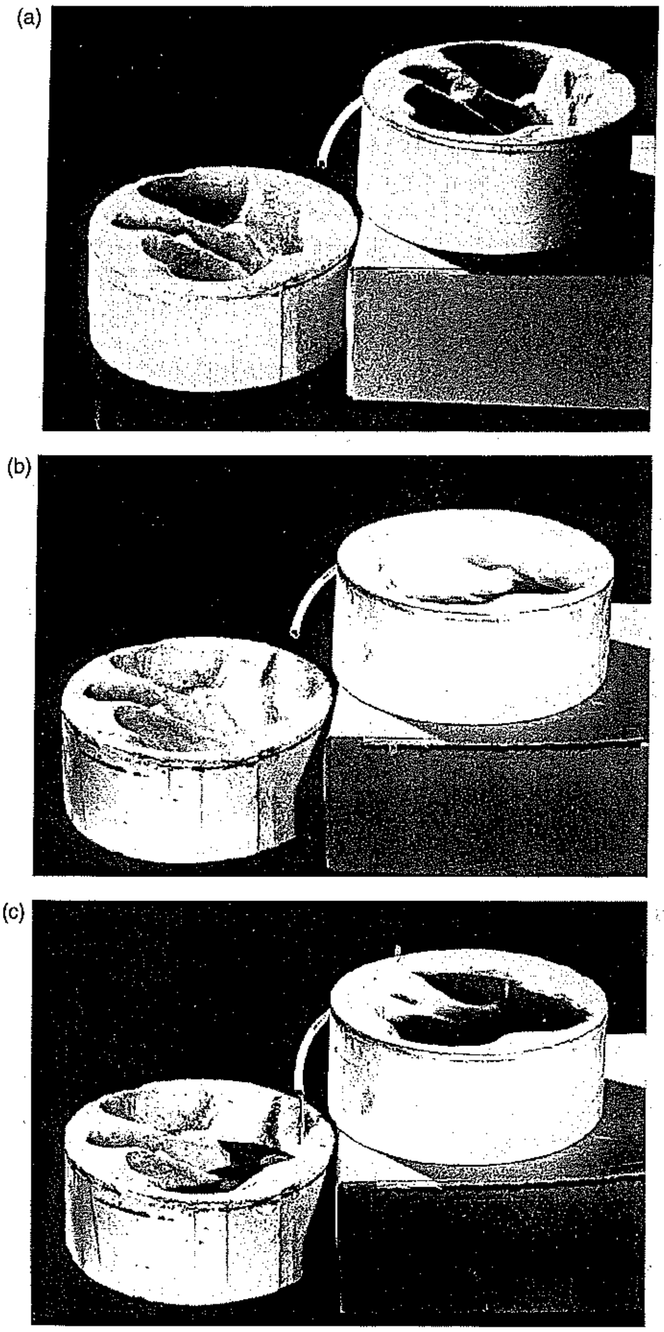


Figure 11.2 "I am happy to offer you some pictures of the wet form of the epigenetic landscape; they have to be looked at in the order 1, 2 and 3." Letter from Thom to Waddington, January 19, 1968

Source: Waddington Archive, University of Edinburgh.

Waddington first imagined the epigenetic landscape as a figurative representation. Then he came to think of it in terms of a material model composed of balls running along valleys controlled by switches. In Thom's plaster model the only dynamical element is introduced by the pouring and flowing of a fluid on the landscapes. This leaves open the genesis and the dynamics of the landscape itself. However, if one takes seriously the dialog between Thom and Waddington, the landscape can be thought of as a dynamical system, with no predetermined representation, but with dynamical and relational characteristics open to exploration.

Thom and Waddington's discussion of dynamical material models motivated the core energy of my teaching and research activities at ENSAD in Paris. Based on the image of the epigenetic landscape and on Thom and Waddington's exchanges, I developed a program of experimentation on morphogenetic design, called the "dynlan-dynamic landscape." We were not interested in what the landscape *represents*, from the point of view of the involved variables or of the specific processes, but in what it *does*, from the point of view of its equilibria, destabilizations, dynamics. Architects, designers, artists, and students involved in the dynlan-dynamic landscape program used performative instead of representational properties to design and build morphodynamical material systems sharing generic dynamical properties with the landscape. The proposed systems are not aimed at illustrating the point of view of Thom or Waddington. Rather, they are devised to shape the implicit sense of "landscape" that underlies their dialogue, which neither figurative representations nor attempts at formalization could satisfactorily grasp. Researchers and students involved in the dynlan-dynamic landscape research program landscapes realized their own versions of a dynamic landscape.[32] Students in the workshop were guided by images of the epigenetic landscape or, more generally, of images of landscape in biology, thus including presentations by researchers working on adaptive or fitness landscapes. A brainstorming session with the scientific researchers aided the formulation of prototypes, conceived of as parametric structures underlying various morphological states. The goal of this design process was to fathom and create families of parametrically variable objects. A set of questions bound to the dynamic morphologies of the landscapes guided us through the process. The "landscape" metaphor—qualified as "adaptive," "epigenetic," or "energetic"—presents a characteristic shape defined by peaks, pits, and cols. Despite the semantic differences of these different landscapes, we asked generic questions, such as: What are the nature and the evolution of equilibria of the landscape? How is its stability and robustness characterized? What is the effect on a landscape of different kinds of perturbations? At what spatiotemporal scale is it suitable to situate such analyses and investigations? What are the variables that are represented by the landscape?

The design of parametrically variable objects brings to mind Deleuze's concept of the *objectile*. However, we realized the parametricism playing directly with the properties of materials in order to create material systems to embody morphogenetic dynamics compatible or inspired by the possible dynamics unfolding in the epigenetic landscape. And, once again, this morphogenetic variability was not bound to the use of mathematical models or digital technology in our experimentation. We did not write any equation, or program. In our experimentation the "morphogenetic" within "morphogenetic design" is not rooted in the digital. We realized parametricism through analog systems. Yet, neither digital parametricism nor analog parametricism can pretend to stand in the place of biological morphogenesis. The idea that different morphogenetic processes—in the living world and in the non-living world, in mathematics—share something is rooted in the paradigmatic works on morphogenesis by Thompson and Turing. For this reason the following section is devoted to an archaeological study of the role of analogy and the use of analogs in the study of morphogenesis.

The "Imaginary Organism," or the Imagination of Forms

Thompson and Turing's anti-teleological position vis-à-vis the genesis of forms—living forms included—is not a reductionism explaining living and non-living forms according to physical materialism. It is instead an attempt to develop a certain theoretical vision in biology based upon the appropriate mathematical theory. As Thompson suggested about the use of mathematics for morphology, it is important to understand what can be shared by the forms of the living and the non-living world, and the use of mathematical analogies can help in this understanding. Thompson both begins and ends *On Growth and Form* with references to the German poet and natural scientist Johann Wolfgang von Goethe, from whom he takes the term "morphology." Goethe famously coined the word, which means the study of natural forms, in the groundbreaking text, *Metamorphosis of Plants* (1790). While for Goethe, mathematics was alien to the study of morphology, Thompson found it essential.[33] The "science of forms," as Thompson called morphology, dealt with "the forms assumed by matter under all aspects and conditions, and in a still wider sense, with forms which are theoretically imaginable."[34] Considered from the point of view of design, Thompson's statement opens up new ways to use morphology and, by connection, physics and mathematics in the theoretical imagination of forms. Mathematical analogies were central to Thompson's thinking. For example, there are several phenomena, from chemical autocatalysis to the growth of an individual or of a population, which in Thompson's work manifest in an S-shaped mathematical curve. However, he specified that this analogy is mathematical, and not physico-chemical.[35] From this we understand that Thompson's use of mathematics and physics is not a reductionist one. There is flexibility here—space left open for the use of analogies.

The use of mathematical analogies in a non-reductionist attitude is also at the core of Turing's "The Chemical Basis of Morphogenesis" (1952), published almost four decades after Thompson's *On Growth and Form*. I argue that Turing's contribution marks a renewal of Thompson's thinking on dynamic mathematical equations. This renewal concerns the link in Turing's work between novelties in mathematical modeling and embryological morphogenesis, the use of numerical calculus as a means to understand pattern formation, and the relationships Turing establishes between analytical and numerical studies.

I also argue that Turing's use of non-linear equations and digital calculus reveals that Turing's approach was not purely mathematical, but was also turned to questions coming from the embryology and theoretical biology of his time, namely from the work of Waddington on the role of equilibria in the study of development. In Turing's model of development, a system of partial differential equations known as reaction-diffusion equations, two interacting chemical substances, diffuse within living tissue. Because of instabilities in this system, what is also referred to as symmetry breaking, there is a spontaneous production of patterns. As Turing stated, the "investigation is chiefly concerned with the onset of instabilities."[36] In other words, Turing explored the mathematical properties of non-linear systems to understand spontaneous pattern formation in nature, and mathematically showed how the instabilities in a process of reaction-diffusion of two interacting chemical substances, expressed by a differential system, can produce spatial patterns because of symmetry breaking.

Turing contributed a novel mathematical model to the study of morphogenesis, but it was not considered by adherents of strict genetic determinism to be pertinent to the genesis of patterns in organisms because he did not account for gene function. Genes do not play a central role in the process described by Turing. For this reason, I argue that Turing's contribution is alien to the genetic determinism of the Modern Synthesis and, by contrast, it is part of a genealogy of research based in the embryology and theoretical biology of his time.

In a related vein, Turing does not connect his developmental mathematics to the then emerging sciences of information and genetics. In 1944, Erwin Schrödinger introduced an informational metaphor in *What is Life?* describing early on the gene as a codescript.[37] Despite the prominence and persuasiveness of Schrödinger's "codescript" at mid-century, Turing makes no mention of it or the incipient understandings of the genetic program. Rather, his theory is based on the study of the symmetry breakings within a system, i.e. its bifurcations, which disrupt the equilibrium of the morphological state. If symmetry breaking is the minimal generative principle needed to understand the production of different forms in Turing's perspective, the main actors of Turing's model are "the morphogens," Turing's neologism referring to substances involved in his equations. Turing explained that "these substances will be called morphogens, the word being intended to convey the idea of a form producer."[38] Turing specified that this term "is not intended to have any exact meaning, but it is simply the kind of substance concerned in this theory."[39] A morphogen is not identified by its physico-chemical properties but by its behavior. The morphogen has a purely relational definition, not a materialistic one. Its actions rather than substance give it definition. Within this framework, the choice and regulation among the different possible vectors of equilibria of the system are catalyzed by the genes, but the genes themselves are not seen as the only determinants creating forms. Turing does not exclude genes from the realm of morphogens. The action of genes in pattern formation is nonetheless indirect: it is a catalyzing action. For Turing the genes define the reaction rates. Turing clarified, "insofar, for organisms with the same genes, they can be eliminated from discussion."[40]

Turing developed his own mathematical view on biology based on certain theoretical debates and experimental research of his time. There is novelty and originality in both sides of his approach, in the biology as well as in the mathematical modeling. One motivated and reinforced the other. Connecting Turing's math to theoretical biology, Waddington's "evocator" is indicated by Turing as an example of morphogen. In Waddington's research an evocator was initially considered as a chemical responsible for induction in the creation of tissue in a living organism.[41] The evocator was a substance present throughout the whole embryo activated in one particular region, the organizer center, by way of a gradient system. Waddington also introduced the concept of competence: for Waddington a material which is capable of reacting to a given inducing stimulus is said to be "competent" for that process of induction.[42] For Waddington, a competent tissue should be thought of as an unstable system with two or more ways of change open to it; the decision as to which way it actually follows being taken by the relevant organizer.[43]

Based on this context, Turing's focus on the study of the onset of instabilities can be seen as a theoretical and mathematical answer to an exigency coming from the biological theorizing of his time: the understanding of the role of unstable systems within embryological development. Turing's theory is a not reductionist one since, to repeat, he is not interested in what morphogens *are*, but in how they *interact*. From this performative understanding of the morphogen, he proposed pattern formation through the study of unstable equilibria.

Turing adopted an analytical approach in the linear approximation. Yet, for the non-linear case this is not in general possible, as Turing was perfectly aware. To overcome this limitation due to the form of his equations, for a particular non-linear case Turing used numerical solutions provided by the Manchester computer.

He explained, "The difficulties are, however, such that one cannot hope to have any very embracing *theory* of such processes, beyond the statements of the equations. It might be possible, however, to treat a few particular cases in detail with the aid of a digital computer."[44] Turing acquired a table of numerical values from the calculations of the computer, from which he imagined the formation of a pattern. In an early instance of a proto-computational model, he called this numerical tablet an "imaginary organism." Turing elaborated, "The first five columns all refer to the same 'variety' of the imaginary organism, but there are two specimens shown."[45] In sum, Turing arrived at his idea of an imaginary organism through a numerical and not an informational metaphor. The behavior of this imaginary organism provides a particular instance of the morphogenetic processes the equations point to. It is not a real organism, but it likely shares some morphogenetic processes with unknown, more complex, real organisms. For Turing, mathematical equations are not enough to provide a complete theory of pattern formation. The combination of the knowledge gained through numerical calculus with the principles described by the mathematical equations allows Turing to provide, if not a complete theory, at least a vision of pattern formation that could be used to interpret the process of pattern formation in real organisms. Within this vision, the imaginary organism is an analog to unknown real organisms.

Conclusion

I have discussed the possible relations between morphogenesis and design both from an epistemological perspective and an empirical one, using the framework of a design studio. Instead of exploring the potentialities of digital technologies, attempting to analyze the success of these practices in extending the domain of what can be materially realized, the approach to the question of morphogenetic design developed in this chapter came out of a different arena: the space in between and outside of the digital. The analysis of Turing's contribution to morphogenesis suggests that the generative principles of morphogenesis grasped by his mathematical equations are theoretically operable both in numerical studies and in real, living organisms. If we translate this consideration into design, this means that the use of the digital *can* in fact provide instances of morphogenetic processes. However, we should not consider the digital as the only access to morphogenetic processes. Parametricism, often thought of as a way to implement morphological research, can be experienced directly by way of analog systems. In the history of architecture and design the use of analog models is certainly not new, as the famous examples of the architects Antoni Gaudí and Frei Otto show. One could think that digital practices encompass what one could do through analogs and that nowadays the use of analogs in architecture and design has become obsolete. I obviously do not agree with this point of view. The archeological study of the work on morphogenesis of Thompson, Turing, and Waddington shows the complexity of the relations between materiality, mathematical models, and digital models. I defend the idea that an approach through analogs still has an intrinsic interest that cannot be reduced to a purely digital approach.

The images of the epigenetic landscape initially piqued my interest as a call for mathematization in theoretical biology.[46] The epigenetic landscape functioned for me and my students as a process-oriented and dynamic systems-based path, which was not simply other than but more accurate than the realm of representation and description. This study revealed that a performative was better than a representational approach. In everyday parlance, the "landscape" designates the thing and the image of the thing—the signified and signifier. The goal of the dynlan-dynamic landscapes research program was to work within a more changeful sense of the term by looking to the dynamical properties and active behavior of designed material systems. The morphological properties of a given landscape, in the process of evolution, can be translated in dynamics that one could try to produce through designed material systems. These dynamics are thus shared by images of landscape (thought as processes) and material systems.

Addendum: Design Studio[47]

We referred to our design studio at ENSAD in 2008 as "A Network of Singularities," which was part of the overarching workshop, "Dynamic and Sensitive Landscapes" (*Paysages sensibles*

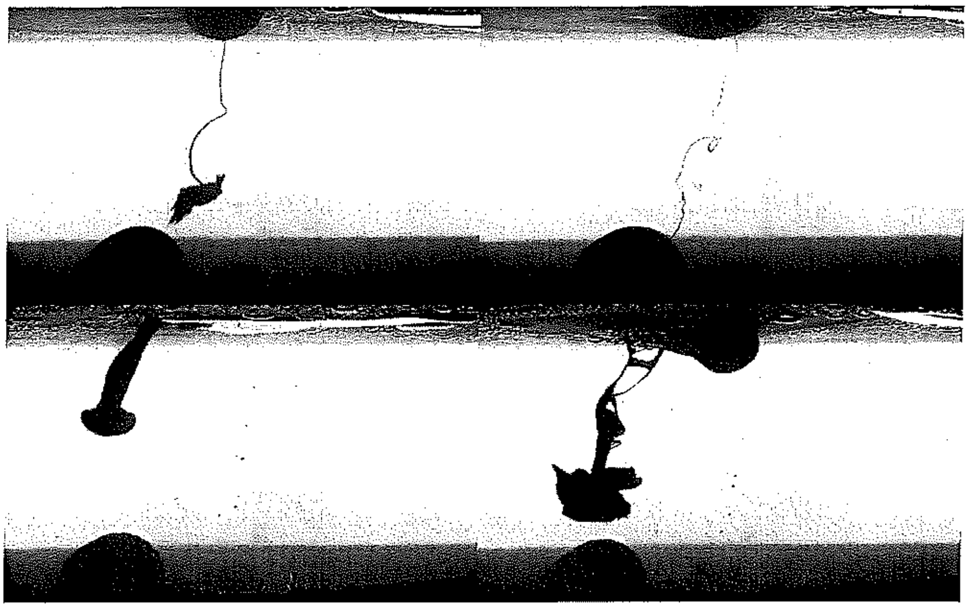


Figure 11.3 "Magnetic Landscape" (*paysage magnétique*), Maia D'Abboville and Ferdinand Dervieux. In the framework of the "Dynamics of a Landscape" workshop

Source: © *ensadlab-dynlan*, ENSAD.

et dynamiques).[48] The workshop was co-directed by Yves Mahieu and me and was inspired by the Waddington–Thom correspondence. We took the notion of singularity as the dynamic unit around which a complex surface of action would be designed. We worked on the dynamics of equilibria, of local minima and maxima, underlying the modification of a complex surface of tense membranes. We calibrated the parameters of the dynamics to obtain a periodic deployment of the surface itself. We further explored interactivity in the interface between the designed system and users through another system of dynamics, called "fluid scenarios" (*fluid scenarii*). This was connected to the system "magnetic landscape" (*paysage magnétique*), realized by two students, Ferdinand Dervieux and Maia d'Abboville, in the framework of the "Dynamics of a Landscape" workshop.[49]

Dervieux and d'Abboville conceived their project based on a generic landscape in which a ball could be a modifiable element, in addition to the undulating landscape. The system exploited the dynamic properties of a magnetic fluid parametrically modulated by magnetic and mechanical constraints. The behavior of the conceived system, in response to user stimuli, raised the following questions: Are there recurrent morphologies in function of external stresses? Can we recognize recurrent histories? Can we return to these morphologies of the recent and deep past? We found the notion of "scenario" useful as it is rooted in the study of dynamic/complex systems transitioning from stability to chaos. We explored responsive dynamics, under the effect of external stresses from a mathematical point of view. When non-linearity is implied, the predictive power of equations is not guaranteed.[50] In order to predict the shifts of this kind of system, equations are not enough: one needs to know the history of the system and its behavior under the effect of the variation of some control parameters. We queried, "How does the system perform in time and under the effect of its parameters variations? Are there scenarios, defined by a generic series of bifurcations that one can recognize?" Our experience of performative design allowed us to explore this set of questions by observing the dynamic behavior of the magnetic landscape (*paysage magnétique*) in response to the user actions.

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Notes

1 Gilles Deleuze, *Le pli. Leibniz et le Baroque* (Paris: Seuil, 1988).
2 Mario Carpo, *The Alphabet and the Algorithm* (Cambridge, MA: MIT Press, 2011), 40–41.
3 Ibid., 142–143.
4 See Achim Menges, "Biomimetic Design Processes in Architecture: Morphogenetic and Evolutionary Computational Design." *Bioinspiration and Biomimetics* 7 (2012): 015003–015013.
5 Carpo, *The Alphabet*, 143.
6 Andrew Hodges, *Alan Turing: The Enigma of Intelligence* (London: Burnett Books, 1983), 431.
7 Peter T. Saunders, "Alan Turing and Biology." *IEEE Annals of the History of Computing* 15, 3 (1993): 33–36.
8 Ibid., 33–34.
9 Ibid., 34.
10 Julian Huxley, *Evolution: The Modern Synthesis* (New York: John Wiley & Sons, 1942), 23.
11 Richard Dawkins, *The Blind Watchmaker* (New York: W. W. Norton & Co., 1986).
12 Tim Ingold, *Making: Anthropology, Archaeology, Art, and Architecture* (Abingdon: Routledge, 2013).
13 Ibid., 67.
14 D'Arcy Wentworth Thompson, *On Growth and Form* (Cambridge: Cambridge University Press, 1917; 2nd edn. 1942, repr. 1945), 7–8.
15 Alan M. Turing, "The Chemical Basis of Morphogenesis." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 237 (1952): 37–72.
16 One can refer to Scott Gilbert, "Epigenetic Landscaping: Waddington's Use of Cell Fate Bifurcation Diagrams." *Biology and Philosophy* 6 (1991): 135–154. See also Conrad Hal Waddington, *An Introduction to Modern Genetics* (New York: Macmillan, 1939) and Conrad Hal Waddington, *Organisers and Genes* (Cambridge: Cambridge University Press, 1940; 2nd edn., 1947).
17 The images of the epigenetic landscape I discuss come from Conrad Hal Waddington, *The Strategy of the Genes* (London: Allen & Unwin, 1957), 29 and 39.
18 The images of the epigenetic landscape I discuss come from ibid.
19 Conrad Hal Waddington, *The Strategy of the Genes* (Allen & Unwin, 1957), 23.
20 Ibid., 29, 36.
21 Ibid., 9.
22 Waddington, for example, was well aware of the contributions of the mathematicians Alfred James Lotka and Vladimir Alexandrovitch Kostitzin. He also quotes extensively the work of Ross Ashby on cybernetics.
23 On this topic see Scott F. Gilbert, "Induction and the Origins of Developmental Genetics," in *A Conceptual History of Modern Embryology*, S. F. Gilbert, ed. (New York: Plenum Press, 1991), 181–206, and Jean Gayon, "La marginalisation de la forme dans la biologie de l'évolution." *Bulletin d'Histoire et d'Épistémologie des Sciences de la Vie* 5, 2 (1998): 133–166.
24 A potential energy surface describes the energy of a system in terms of certain parameters, usually even not necessarily the positions of the elements composing the system. It is usually visualized as a hilly landscape: for a system with two degrees of freedom, the value of the energy (the height coordinate of the landscape) is a function of two coordinates.
25 See Peter T. Saunders, "The Organism as a Dynamical System", in *SFI Studies in the Science of Complexity, Lecture Notes*, vol. 3, F. Varela and W. Stein, eds. (Reading, MA: Addison Wesley, 1993), 41–63. J. M. W. Slack, "Conrad Hal Waddington: The Last Renaissance Biologist?" *Nature* 3 (2002): 889–895.
26 See René Thom, "Une théorie mathématique de la morphogenèse," in *Towards a Theoretical Biology I*, Conrad. H. Waddington, ed. (Edinburgh: University of Edinburgh Press, 1968), 152–166; repr. in

René Thom, *Modèles mathématiques de la morphogenèse* (Paris: Christian Bourgeois, 1980); English trans. *Mathematical Models of Morphogenesis* (Chichester: John Wiley & Sons, 1983).

27 A detailed analysis of this correspondence can be found in S. Franceschelli, "Morphogenèse, stabilité structurelle, et paysage épigénétique," in *Morphogenèse. L'origine des formes*, Annick Lesne and P. Bourgine, eds. (Paris: Belin, 2006), 298–308. English trans. "Morphogenesis, Structural Stability and Epigenetic Landscape," in *Morphogenesis. Origin of Patterns and Shapes*, Annick Lesne and P. Bourgine, eds. (Berlin: Springer Complexity, 2011), 282–293.

28 Letter from René Thom to Conrad Hal Waddington, December 11, 1967 (Waddington Archive, University of Edinburgh). In a further publication René Thom presents and discusses this clay model of the epigenetic landscape, calling it "The Hydraulic Model." See René Thom, "Topological Models in Biology." *Topology* 8 (1969): 332–333.

29 A potential well in physics is as a region surrounding a local minimum of potential energy.

30 The first and the second image composing Figure 11.2 have been published in Thom, "Topological Models" as plates V and VI.

31 Waddington's answer to Thom, December 19, 1967 (Waddington Archive, University of Edinburgh).

32 I've enlarged on these experiences, realized in the framework of workshops held at ENSAD, and given details on their context in Sara Franceschelli, "Morphogenesis and Dynamical Systems. A View Instantiated by a Performative Design Approach," in *Imagine Math 2. Between Culture and Mathematics*, Michele Emmer, ed. (Milan: Springer Verlag, 2013), 117–126.

33 See, for example: "To treat the living body as a mechanism was repugnant, and seemed even ludicrous, to Pascal; and Goethe, lover of nature as he was, ruled mathematics out of place in natural history" (Thompson, *On Growth and Form*, 2), and "We have learned in so doing that our own study of organic form, which we may call by Goethe's name of Morphology, is but a portion of that wider Science of Form which deals with the forms assumed by matter under all aspects and conditions, and, in a still wider sense, with forms which are theoretically imaginable" (ibid., 1026).

34 Ibid.

35 I quote Thompson at length: "It is sufficiently obvious that the normal S-shaped curve of growth of an organism resembles in its general features the velocity-curve of chemical autocatalysis, and many writers have enlarged on the resemblance; but the S-shaped curve of growth of a population resembles it just as well. When the same curve depicts the growth of an individual, and of a population, and the velocity of a chemical reaction, it is enough to show that the analogy between these is a mathematical and no a physico-chemical one." Ibid., 258.

36 Turing, "Chemical Basis," 37.

37 Erwin Schrödinger, *What is Life?* (Cambridge: Cambridge University Press, 1944).

38 Turing, "Chemical Basis," 38.

39 Ibid.

40 Ibid., 39.

41 Waddington developed this notion with biologist Joseph Needham, while they worked on embryological induction following the research line opened by Hans Spemann's induction. Some words on the context are here necessary. For Spemann induction was the process by which the identity of certain cells influences the developmental fate of the surrounding cells. Another important notion in this context was the Spemann–Mangold organizer. An organizer is a cluster of cells in the developing embryo of amphibians that induces the development of the central nervous system. For more detail and an analysis of Waddington's works on induction, in the historical context of his research at the interface of genetics and embryology, see Gilbert, "Induction."

42 Conrad Hal Waddington, "Experiments on the Development of Chicken and Duck Embryos." *Philosophical Transactions of the Royal Society of London. Series B, Containing Papers of a Biological Character* 221 (1932): 179.

43 Conrad Hal Waddington, "The Origin of Competence for Lens Formation in the Amphibia." *Journal of Experimental Biology* 13 (1936): 86–91.

44 Turing, "Chemical Basis," 72.

45 Ibid., 63.

46 I've elsewhere defended the idea that they insert themselves in the history of the use of dynamical systems theory in biology: Sara Franceschelli, "Some Remarks on the Compatibility between Determinism and Unpredictability." *Progress in Biophysics and Molecular Biology* 110, 1 (September 2012): 61–68.

47 More detail can be found in Franceschelli, "Morphogenesis and Dynamical Systems."

48 A film of the behavior of this system can be found at: www.youtube.com/watch?v=E6Nuik4WPtQ. Accessed July 25, 2016.

49 A film of the behavior of this system can be found at: www.youtube.com/watch?v=w09iCUQ39OA. Accessed July 25, 2016.

50 The term "scenario" here employed is inspired by the term introduced at the end of the 1970s and beginning of the 1980s by several groups of physicists working on the road of transition to chaos. In this context, the notion of scenario was defined as a sequence of bifurcation undergone by a system under the variation of a control parameter.

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