

Article

Turing's Biological Philosophy: Morphogenesis, Mechanisms and Organicism

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Abstract: Alan M. Turing's last published work and some posthumously published manuscripts were dedicated to the development of his theory of organic pattern formation. In *"The Chemical Basis of Morphogenesis"* (1952), he provided an elaborated mathematical formulation of the theory of the origins of biological form that had been first proposed by Sir D'Arcy Wendworth Thompson in *On Growth and Form* (1917/1942). While arguably his most mathematically detailed and his systematically most ambitious effort, Turing's morphogenetical writings also form the most thematically self-contained and least philosophically explored part of his work. We dedicate our inquiry to the reasons and the implications of Turing's choice of biological topic and viewpoint. We will probe for possible factors in Turing's choice that go beyond availability and acquaintance with *On Growth and Form*. On these grounds, we will explore how and to what extent his theory of morphogenesis actually ties in with his concept of mechanistic computation. Notably, Thompson's pioneering work in biological 'structuralism' was organicist in outlook and explicitly critical of the Darwinian approaches that were popular with Turing's cyberneticist contemporaries—and partly used by Turing himself in his proto-connectionist models of learning. Resolving this apparent dichotomy, we demonstrate how Turing's quest for mechanistic explanations of how organisation emerges in nature leaves room for a non-mechanist view of nature.

Keywords: Alan M. Turing; D'Arcy Wendworth Thompson; morphogenesis; Darwinian evolution; modern synthesis; mechanism; organicism; explanations in science



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1. Introduction

Alan M. Turing's last published work and some posthumously published manuscripts were dedicated to the development of his theory of organic pattern formation. In his 1952 *"The Chemical Basis of Morphogenesis"* [1], Turing provided an elaborated mathematical formulation of the theory of the origins of biological form first proposed in 1917 and 1942 by Sir D'Arcy Wendworth Thompson in *On Growth and Form* [2]. In this influential work in developmental biology, Thompson highlighted the complexity of organic forms and their accessibility to mathematical descriptions while playing down the importance of mechanisms of natural selection. Turing's aim was to devise a computer-implementable formulation of Thompson's account of organic pattern formation, asking how the intricate patterns of animal anatomy, plant phyllotaxis and other common biological structures develop from genetically homogenous cellular matter.

Turing's morphogenetic writings bear the least obvious connection to his endeavours in the foundations of mathematics and of what would become computer science while being geared towards computer-implemented solutions (e.g., in [3]; see also Swinton's analysis in [4]). At the same time, these writings form the least philosophically explored part of Turing's work, whose further development was cut short by his untimely death in 1954. While exerting significant and lasting influence in developmental biology, Turing's theory was largely ignored by most scholars outside botany and embryology for several

decades. However, from the late 20th century onwards, morphogenesis has seen a revival and a much broader audience, with Turing's 1952 paper having become his second-most cited publication.

When it comes to tracing the origins of Turing's specific concern with the phenomenon of morphogenesis, the received view seems to be that "The reason why the mathematician Turing got interested in the mechanism of biological morphogenesis is unknown" ([5], suppl. materials). This claim does not seem entirely true in light of the available biographical accounts of Turing's influences [6,7], although these accounts still leave something to be desired. However, that claim of ignorance appears justified with respect to more systematic reasons and their larger history and philosophy of science context. This is the research gap that we are seeking to close. The questions to be investigated in our essay are: First, what motivated Turing's choice of biological topic and viewpoint? Second, is there a significance to Turing's theory choice that might go beyond the circumstances of availability of, acquaintance with, and subjective preference for Thompson's approach? Above and beyond describing contextual factors that informed his choice, we identify theoretical and methodological reasons, only some of which Turing himself made explicit, but all of which bear some metaphysical implications.

Our contribution is structured as follows: We begin by presenting an outline of Turing's morphogenetic theory and its key premisses (Sections 2.1 and 2.2, respectively). Second, we briefly retrace Turing's early intellectual biography and influences from biology (Section 3.1) before investigating the implicit and explicit theoretical factors behind Turing's choice of the morphogenetic project in some detail (Sections 3.2 and 3.3, respectively). Our discussion in Section 4 will focus on the bearing of Turing's concept of mechanism—and its possible limitations—on his views of life.

2. Turing's Contribution to Biological Modelling

Turing's work on morphogenesis was one of the first detailed applications of mathematical modelling methods to organismic biology. Besides the obvious case of Thompson [2], one earlier application was offered by Ludwig von Bertalanffy [8], but it is unlikely that Turing was aware of this work. Classical mathematical models in population genetics—and therefore in an altogether different biological subdiscipline—were provided by Ronald Fisher, J.B.S. Haldane and Sewall Wright [9–11]. Turing's theory of organic pattern formation was also one of the first attempts to explain in a non-teleological fashion, purely by reference to physico-chemical laws, how a homogeneous organic structure can develop into a morphologically non-homogenous, complex living system. His approach found a considerable degree of adoption in developmental biology. Some authors claim that these accomplishments made Turing [1] "one of the most influential theoretical papers ever written in developmental biology" ([12], p. 183), and that "Turing seems to have identified one of nature's general mechanisms for generating order from macroscopic uniformity and microscopic disorder." ([13], p. 9). Likewise, "Turing sought an explanation of how a chemical soup of molecules in an embryo could possibly give rise to a biological pattern", and thereby "to provide an argument for the generation of 'order-from-disorder'" ([14], p. 9). Turing's proposed mechanism has been partly empirically validated with respect to biological explanations of chemical patterns (see, e.g., [15,16]) and their effects on morphological patterns of skin markings (see, e.g., [17]) as well as in seashells [18]. Raspopovic and colleagues [19] have argued for Turing-type mechanisms in digit patterning. More broadly, his 1952 paper is "now recognized as an early essay in *A-Life*"—*avant la lettre* ([20], p. 1262). Turing's morphogenetic ideas have also been applied outside the domain of biology, in areas such as physics, astrophysics, or hydrodynamics [12] as well as in economics [21]. With respect to implementation in computer models, it has been demonstrated that patterns analysed by Turing can be produced with Universal Turing Machines [22].

When Turing adopted Thompson's theory of organic pattern formation, he chose an explicitly non-Darwinian, structuralist, and holistic approach to biological phenomena over the more mechanistic, individualistic and explanatory reductionist Darwinian accounts

that were at least as well established at the time. Where the overall description of a system and the relations between its elements are considered necessary for an explanation in structuralism, the properties and behaviours of its elements are deemed explanatorily sufficient in mechanism. Remarkably, mechanistic Darwinian accounts were more popular with Turing's cyberneticist colleagues, such as W. Ross Ashby, with whose early work (e.g., [23,24]) he was acquainted through his membership in the *Ratio Club* (for a historical account of that club, see [25]; for comparisons between Ashby's and Turing's accounts, see [26,27]; we will discuss more details of Turing's partial alignment with early British cybernetics in a future paper). Turing himself adopted quasi-Darwinian accounts to some extent, when referring to mechanisms of selection in his proto-connectionist model of intelligent machinery ([28], p. 455). However, this inquiry does not address questions of the anatomy of the brain but processes of learning from environmental stimuli. Like other early cyberneticists, Turing used Darwinian mechanisms of variation and natural selection as an analogy in modelling learning processes as processes of random variation in the organism and their selection by the environment. As far as the modelling of biological phenomena was concerned, Turing would choose a different path, which most of cybernetics would come to appreciate only later. However, despite the differences in approach and choice of topic, there is no strict methodological dichotomy between Turing's reading of Darwinian mechanisms and his adoption of Thompson's theory. On both sides, he would invoke mechanistic explanations in a basic (and contemporary) sense, which consider the elements of some superordinate structure and their coordinated interactions in order to develop insights into the system's higher-level properties and behaviours (see, e.g., [29]). We will return to this topic in our discussion of mechanistic explanations in Section 4 below.

2.1. Theoretical and Methodological Presuppositions

The general aim of Turing's development of the theory of morphogenesis was an "explanation of the inception of pattern in living organisms" ([30], p. 38), that is, to show how a collective of cells or a tissue that is at first homogenous can spontaneously, after a very slight loss of stability, develop in a self-organised manner, without outside interference, into a complex, novel structure with a regular pattern of differentiated, heterogeneous elements. Turing's more specific aim was to "[...] discuss a possible mechanism by which the genes of a zygote may determine the anatomical structure of the resulting organism" ([1], p. 5). In doing so, however, his aim was explicitly *not* to account for the concrete underlying genetics or biochemistry of pattern formation. This kind of substrate neutrality is the first and most obvious negative presupposition of his theory. Although Turing does not explicitly derive this concept from his notion of implementing computational routines in physically distinct systems [31], which has become known as 'machine state functionalism' or 'multiple realisability' [32], it at least closely resembles this notion. The minimum extent to which Turing's abstraction from concrete biochemical processes actually bears on this notion is the possibility he envisioned of using digital computers for modelling these processes in a different medium.

The domain of computable functions, in Turing's terms, is exhausted by the functions that are 'effectively calculable' in such a way that they can be solved, in principle, by a mechanical procedure, where, first, an effective method of calculation consists in a finite set of exact instructions that produce a correct solution to a function in a finite number of discrete steps. Second, a mechanical procedure in this context refers to the general strategy of breaking down higher-order logico-mathematical operations into elementary arithmetical routines that could be accomplished with only a modicum of mathematical skills—either by human 'computers' or by a certain class of 'discrete state' machines. Any way of solving a logico-mathematical problem that adheres to these abstract mechanistic principles is computational, independent of the way in which it is physically implemented. Conversely, any logico-mathematical problem that cannot be solved in this fashion is uncomputable. In analogy to these principles, Turing purposefully abstracted from real-world biochemical and genetic processes, grounding his model in the interactions between

idealised biochemical substances (*morphogens*; from Classical Greek: form originators) that can be described in such a way that they might ultimately be given a computational formulation. We discuss the possible consequences of this presupposition on the choice of morphogenetic modelling in Section 3.2.

Using a system of partial differential equations, Turing described the process from an initially uniform distribution of morphogens across the system into waves of differing concentrations, where the possible transformations are given by the known laws of physics. Thus understood, Turing's theory of morphogenesis incorporates two further negative presuppositions besides the condition of substrate neutrality. All three presuppositions directly speak to the biological debates of his time and are crucial to an understanding of Turing's approach and its philosophical implications (to be discussed in more detail in Section 4).

The second negative presupposition is that morphogenetic processes shall be explainable without reference either to a specific teleological organisation of living forms or to 'special' laws of nature that exclusively pertain to the domain of life (see also [33,34]). Turing considered the known laws of physics and chemistry sufficient for an explanation:

Unless we adopt vitalistic and teleological conceptions of living organisms, or make extensive use of the plea that there are important physical laws as yet undiscovered relating to the activities of organic molecules, we must envisage a living organism as a special kind of system to which the general laws of physics and chemistry apply. ([30], p. 45)

Not even the laws of genetics—if they had been fully understood at the time—or other parochially biological laws needed to be invoked. More specifically and positively, the transformations involved in morphogenetic processes can be described by recourse to changes of velocity and position as described by Newton's laws of motion, to elasticities, osmotic pressures, and diffusion reactions ([1], p. 37–38).

The third negative presupposition of Turing's theory, complementary to the second, is its indifference towards Darwinian mechanisms of random variation and natural selection as sources of design in animate nature. Although he did not deny the existence of these mechanisms, and although he explicitly discussed analogues of Darwinian mechanisms in the context of learning [28], Turing did not at all consider the possible role of Darwinian evolution in the context of pattern formation. He probably deemed Darwinian mechanisms either insufficient for or irrelevant to an explanation of pattern formation, while he considered his mathematical formalism of diffusion reactions wholly sufficient.

2.2. Turing's Diffusion-Reaction Theory of Morphogenesis

The "idealised and simplified" model of a biological system proposed by Turing ([35], p. 43) incorporates a pair of two morphogens, which we will refer to here as u and v , diffusing through a medium and taking part in a chemical reaction in which one can be regarded an activator (u)—a substance that is a direct or an indirect catalyst for its own formation and for production of the other, v , as an inhibitor that causes a destruction of u .¹ At the initial stage, the organism is morphologically symmetrical with the morphogens being homogeneously distributed and production and inhibition rates enabling a stable equilibrium. Turing gave a simplified example in which the rate of production of u was equal to $5u - 6v + 1$ and the rate of production of v was $6u - 7v + 1$. If the initial concentration rates of u and v in two adjacent cells are identical and equal to 1, as in Turing's example, then the change of concentration in the dynamic system of reactions that lead to the production of the two morphogens is equal to 0 for both u and v . The system is in equilibrium.

The state of the system of morphogens without diffusion is represented by a system of differential equations that does not contain a diffusion term:

$$\frac{du}{dt} = f(u, v), \quad \frac{dv}{dt} = g(u, v)$$

In this set of equations, f and g represent rates of production functions. Turing's idea was to first determine a steady (time-invariant) solution that represents its initial homogeneous state in which morphogen concentration does not change:²

$$f(u^*, v^*) = g(u^*, v^*) = 0$$

Turing then proceeded under the assumption that an extremely small perturbation in the concentration rates of morphogens might occur, where the precise nature and origin of that perturbation remain outside the scope of his otherwise deterministic model. In this sense, it is an extraneous or even random factor whose presence is nonetheless central to the theory. The perturbation might be triggered, for example, by Brownian motion, by minor irregularities of form or by interference from neighbouring structures ([1], p. 66). These and similar factors effect a departure from homogeneity in the solution and a diffusion reaction, which yet initially remains near the homogenous steady state. The dynamics of the reactions between morphogens is represented by a system of partial differential equations that now include a diffusion term:

$$\frac{\partial u}{\partial t} = f(u, v) + D_u \Delta u, \quad \frac{\partial v}{\partial t} = g(u, v) + D_v \Delta v$$

In this set of equations, D is a matrix of constant diffusion coefficients or, in Turing's terminology, "diffusion constants". They abstractly represent some physical property of the tissue, which can be more concretely described as the resistance it poses to the flux of a given morphogen. This property influences the rate of change in morphogen concentration. Such a system may remain stable, with concentration rates oscillating close to a steady state. However, Turing was interested in the conditions under which such diffusion near the steady state leads to a breakdown of the dynamic equilibrium and initiates a process of progressive departure from homogeneity of morphogen concentration rates in the tissue.

Under the simplifying assumption of linearity of the regime of reactions, Turing solved the equations to find that a system that becomes unstable and progressively departs from its initial steady state can over time asymptotically converge on several new states of steady or stable equilibria that establish spatial patterns of morphogen concentration in the tissue. In some of these cases, three or more morphogens are involved. The key features of the theory remain intact in these cases ([1], p. 46). The system that was "[...] of greatest interest and has most biological application" ([1], p. 52) was the one whose initial conditions lead to the formation of a steady state with "stationary" waves of morphogen concentrations with finite wave-length. This type of end-point equilibrium presumably has the most direct bearing on known biological systems ([1], pp. 67–68). Turing thought of morphogens as the chemicals responsible for the generation of anatomical structures, organs or all other sorts of organic patterns in locations where they are present in sufficient density. His mathematical theory predicted some of the key properties and behaviours of the real biochemistry of pattern development in nature, at a time at which empirical validation was not yet forthcoming (as Turing and Wardlaw [30], p. 46 were aware of).

The example of a system for which Turing provided details and for which he calculated wave-pattern formations was that of a ring of 20 cells. He considered this particular example because "[...] systems that have the same kind of symmetry as a ring are extremely common" ([1], p. 68). Turing gave an example of *Hydra's* head, which displays circular symmetry in the initial stages of its development. The wave of activator concentration present along the ring potentially explains the break of the head's symmetry, when tentacles start to emerge from the ring in places that can be regarded regions of activator concentration. Another example of the application of the ring model were the whorls on the cylindrical stem of Woodruff (*Asperula odorata*), as well as young root fibres in plants. About flowers in general, Turing said "[...] it is probable that there are many species for which this 'waves round a ring' theory is essentially correct" ([1], p. 69). He suggested that the phenomenon of phyllotaxis can be explained by the same model of stationary waves in two dimensions.

After completing the formulation of his theory in 1952, Turing worked on the inception of patterns in plant phyllotaxis and in florets, with particular focus on those patterns which follow a Fibonacci sequence [35].

One of the remaining problems for Turing's theory was that growth processes themselves may change the observed dynamics of pattern formation mechanisms. In his fragmentary "Outline of the Development of the Daisy" [36], Turing proposed a dynamic morphogenetic model by supplementing the original formulation with a spatiotemporal term that grasps the variation over time of the geometry of the area in which some morphogenetic process takes place, where that variation over time is caused by the growth of the underlying tissue. A more rigorous and thorough incorporation of this dynamic factor into Turing's morphogenetic models was developed almost 50 years after his death [37]. However, it did not alter the fundamental characteristics of these models.

3. Reconstructing Turing's Choice

At first sight, Turing's mathematical theory of morphogenesis is a significant departure both from his theory of computability and from the various forays into machine intelligence that he based on it, first and foremost his proto-connectionist models in [28]. In relying on partial differential equations and continuous functions, his theory of organic pattern formation is mathematically distinct from his theory of computability. In not relying on mechanisms of random variation and deterministic selection, Turing's theory is biologically distinct from his forays into connectionism. Before arguing why this diagnosis is pertinent but of limited purchase, we will reconstruct Turing's reasons for embarking on the morphogenetic project. Some of them will be contextual and biographical (Section 3.1), some of them are founded in theoretical concerns, part of which are implicit (Section 3.2) and others explicit (Section 3.3). It should become clear that Turing's morphogenetic project was not motivated by the ostensible methodological opportunism encapsulated in his observation that his "mathematical theory of embryology [. . .] yields more easily to treatment" than information processing in the human brain [38]. In particular, he expected morphogenesis to be one—if not *the*—paradigm of explaining goal-directed phenomena in non-teleological terms that provides part of the groundwork for his substantial cognitive inquiries, while not fully explaining them.

3.1. Intellectual Biography and Influences

There was a drawing by Turing's mother showing her son as a school age boy "watching the daisies grow", as the caption says, rather than continue to play a game of hockey [4,39]. This drawing attests to an early and genuine fascination with the plant's structural patterns and the growth processes towards that pattern. This observation alone might not suffice to convince us if not for the fact that Turing later got well-acquainted with Sir D'Arcy Thompson's *On Growth and Form* [2]. At the time, this book presented the authoritative account of morphogenetic processes, including plant phyllotaxis [4]. It was the paradigm of mathematical discussions of biological structures available at the time. However, Turing's biographical route to this treatment of organic growth would turn out to be indirect in an instructive way, as it would not remain in the field of biology.

The earliest piece of evidence for Turing's profound interest in physiological development, extensively cited by Hodges [6], is that at the age of 10, young Alan was presented with a children's science book titled *Natural Wonders that Every Child Should Know* by Edwin T. Brewster—which Turing reported to have been a revelation to him ([6], pp. 16–18). The key fact for our argument is that this book was dealing with topics of "General Physiology" in an expressly and rather literally mechanistic fashion, representing organisms as machines construed out of "little living bricks", which in the process of organic growth "divide into half bricks, and then grow into whole ones again." However, Brewster admitted, "how they find out when and where to grow fast, and when and where to grow slowly, and when and where not to grow at all, is precisely what nobody has yet made the smallest beginning at finding out" (as quoted in Hodges [6], p. 17). Explanations of these processes that strived

for a degree of scientific rigour that was missing from earlier speculative accounts—but hoped for by Brewster—were only being developed at the time of his writing. Thompson’s was one of these accounts.

In parallel to his childhood interest in physiological development, Turing developed a keen and partly very practical inclination towards chemistry. This development is well-documented in letters that he wrote to his parents throughout his school age (at Sherborne, 1924–1931). Turing first expressed an interest in chemical analysis in a 1924 letter, two years after he received *Natural Wonders*. Inspired by that book, he asked his parents to provide him with the chemical names and formulas for those substances which participate in the chemical transformation of carbon monoxide in the blood, in order to learn how the process actually runs [40]. Having been presented with the opportunity to conduct first chemical experiments by his parents that same year ([6], p. 25), he continued to express interest in conducting chemical experiments in 1925 [41] and producing substances by himself in 1926 [42]. In his senior school years (1929–1930), Turing also developed an interest in physics both at fundamental (quantum theory) [43] and generalised levels (astrophysics) [44], which led him to consider some related metaphysical problems. There is a list of books that Turing borrowed—and at least partly read—from his Sherborne public school library [45]. That list contains chemistry and physics books of some heft as well as lighter treatments of logico-mathematical topics. It does not contain any readings in biology though. This observation is in keeping with the conspicuous absence of any evidence that Turing’s school-age interests in natural science after *Natural Wonders* would have included evolution, population biology or natural history more broadly.

Turing’s scientific interests partly changed when he was a student at Cambridge (1931–1936). Probably during this time, but certainly before the outbreak of the Second World War, he was introduced to Thompson’s *On Growth and Form*. However, even Andrew Hodges’ detailed and authoritative biography [6] remains remarkably unspecific about when precisely and by what route this happened, thereby demarcating a field for further inquiries. By way of apology, he admits in the preface to the 2014 re-edition of *The Enigma* that the importance of Turing’s morphogenetic work would only come to be properly appreciated well after its first publication in 1983 ([6], p. xx) At any rate, there are some indications that Turing was introduced to Thompson’s work by Conrad Hal Waddington, an influential if controversial developmental biologist who worked at Cambridge at the time of Turing’s studies. There are conflicting accounts on whether Turing and Waddington got to personally know each other during that time: Wolfram [46] assuredly claims they did, whereas Ball [13] considers this unlikely. Unfortunately, neither author supports their claims with evidence or sources. What is certain, however, is that Waddington would later become one of merely three biologists to be cited in Turing [1], and that he critically commented on Turing’s paper in a letter. (Thompson was the second biologist to be cited in [1], of course, and American zoologist Charles Manning Child the third.) Other potential acquaintances that might have led Turing to Thompson include Joseph Woodger and John Desmond Bernal, both of whom, as Waddington, became members of the card-carrying organicist *Theoretical Biology Club*. All three biologists were influenced by the metaphysics of Alfred North Whitehead—an author on Turing’s school-age reading list.

By whatever route Turing got acquainted with Thompson’s work, the observation remains warranted that Thompson provided the general problem and solution strategy to which Turing [1] offered a more specific answer: By what laws of nature does biological form arise? Those laws are above all physical laws that can be fully explicated in mathematical terms and need not invoke Darwinian natural selection. However, first, Turing’s non-linear differential equations came from a different domain of mathematics than the geometric principles laid out by Thompson (as Boden [20], p. 1258 observes). Second, Turing’s equations focused on the incipience of organic forms—the gastrulation of the blastula—that were out of reach of Thompson’s laws of form, which addressed the growth of the organism at more advanced stages ([20], p. 1257). Most notably, Thompson relied on a tradition of German *Naturphilosophie* that cannot be expected to have been

within Turing's domain of knowledge but that might have indirectly informed some of his preconceptions: Johann Wolfgang Goethe's "rational morphology", according to which all organisms develop in accordance with archetypal patterns. Goethe's archetypes are ideal forms that as such do not exist in material nature but are structuring principles embodied in real organisms. An identical archetype may be embodied in a multitude of *prima facie* dissimilar but related organisms in a multitude of systematic transformations. For example, any vertebrate's limbs—from a bird's wings to a human arm—are transformations of the limbs of the vertebrate archetype. While, according to Goethe, archetypes testify to a higher-order goal-directed organisation of life—and ultimately not only to vitalist but also to divine principles—Thompson's 'secularised' version retains the mathematical abstraction of archetype theory, letting geometrically described physical constraints assume the place of purposeful organisation. Although in partly different terms, Turing's approach would follow this lead.

In sum, the remarkable traits of Turing's intellectual upbringing are, first, that his interest in biology was strongly focused on developmental biology from the very beginning. Although it cannot be said that childhood fascinations determine one's adult interests as a matter of principle, in Turing's case the developmental leitmotif seems to have recurred and, if anything, only deepened over time. Second, the development of his biological interests was routed through chemistry, including some amateur experimental practice as a public-school student, plus some physical theory. Third, however, his re-encounter with developmental biology as a university student associated him with a camp of biologists with a markedly organicist outlook, in part self-confessed (Waddington), in part less so (Thompson), but in either case not untypical for this biological subdiscipline at that time, when Darwinian evolution was not a popular doctrine. This set of influences would predispose Turing for an inquiry in biology that, as we will demonstrate, was congenial to his mathematical inquiries in a less than obvious but compelling way while creating a tension between an overall organicist research programme and his specific conception of computational mechanism.

3.2. *Implicit Theoretical Factors*

As was already noted in Section 2, Turing [28] entertained the notion of evolving machines. His idea was that a machine's behaviour might simulate aspects of processes in the brain in a proto-connectionist fashion that bears analogies to Darwinian evolutionary mechanisms. From an initially 'unorganised' state in which conditions are still randomly or quasi-randomly distributed, the machine acquires 'organisation' through iterated rounds of variation in 'initial conditions' and selection *vis-a-vis* new input. In addition, Turing considered the preceding process of selecting a 'child machine' with proper initial conditions partly analogous to mechanisms of Darwinian evolution ([47], p. 460–461). Here, the question is what principles such as predetermined rules of reasoning, behaviour, or other types of definitions and imperatives, have to be 'built into' the child machine, so as to pre-organise it in elementary fashion before it is subject to learning.

If these analogues of Darwinian mechanisms, vague and generic as they may be, seemed workable in modelling the behaviour of the human brain, one might expect them to have their original, non-analogous domain of application in the modelling of evolved organisms, in particular in explanations of the emergence of the basic biological patterns that constitute an organism. Given the emphasis on the role of physico-chemical laws in pattern formation in Turing's and Thompson's theories, and given Turing's emphasis on a precise mathematical formulation, it would be intuitive to assume that there is a role to play for similarly formulated laws of variation and natural selection to shape the developmental processes and the developed structure of an organism. *Prima facie* at least, providing evolutionary explanations of organic pattern formation seems feasible in principle and even something that Turing could naturally follow. Why then did he not choose to explain pattern formation at least in part by reference to some evolutionary conceptions—in terms either of alternative or of complementary mechanisms to his reaction-diffusion model?

After all, there was no necessity to prefer one explanation of pattern formation over the other. Both were equally possible and legitimate. The discussion in the previous subsection might suggest a short and simple answer as to why Turing chose one of these paths: He did not embark on a Darwinian evolutionary explanation of organic forms because he was more interested in chemistry than in population biology and because he read Thompson, not Darwin. This short and simple answer might not be false *per se*, but there might be deeper, more compelling and less circumstantial reasons. Some of them have to do with the state of biological theorising at the time of Turing's writing, others with the particular bearing of his mathematical approach on the phenomenon in question.

With respect to the state of biological theory, a phenomenon can be deemed amenable to an explanation if and when, first, the objects and processes to be explained are already at conceptual and empirical disposal and, second, if and when the features of the system or mechanism supposedly responsible for the properties of the explanandum are well-defined. When considered from this perspective, the target objects of Turing's mathematical theory of morphogenesis were readily definable and the developmental dynamics to be explained observable. The explanandum was an intuitively perceivable and sharply delimited entity—an individual organism, observed over the course of its stages of ontogenetic development. In turn, in order to provide an explanatory hypothesis for this phenomenon, it was possible for Turing to refer to already satisfactorily well-defined physical and chemical features of an organism, even in absence of, and abstraction from, the concrete details of their realisation. Accordingly, both the explanandum and the explanans were sufficiently accessible empirically and sufficiently defined conceptually to allow for the formulation of an explanatory hypothesis concerning organic pattern formation.

These conditions cannot be assumed to fully apply to evolutionary explanations in Darwinian terms at the time of Turing's writing. More precisely, evolutionary biology was only in the process of becoming precise enough—in terms of definition of both the explanandum and the explanans—to provide tenable explanations of its phenomena. Even then, some limitations remain.

First, the proper object, or target system, of an evolutionary explanation cannot be an individual organism, because natural selection can only act on populations of organisms over a number of generations. In this respect, Darwinian explanations of organic pattern formation would have had to—and in fact did—take an entirely different route than that chosen by Turing, namely through histories of selection for the effects of variant traits in a population under a given set of environmental conditions, where these traits were not typically identified as elementary and delimited organic structures but as more higher-order structures singled out by reference to their effects. Hence, Turing's morphogenetic model was out of the range of evolutionary explanations to begin with, whereas his quasi-evolutionary conception of intelligent machinery [28] lacked one key element of an evolutionary analogy because it was based on the iterated replacement of one single state by its modified version in one individual.

Second, a population of organisms whose forms are within a certain range of variability is either unobservable, if considered as a hypothetical model population, or it is difficult to delineate. The latter is a perennial problem of evolutionary biology. Populations can be defined by reference to a common ancestry, to geographic boundaries or to interbreeding relations. Because all three concepts face challenges in terms of delimiting their concrete extensions and general theoretical specifications (see, e.g., [48]), populations are much more difficult to individuate than a single, observable organism.

Third, a similar constraint applies to the elements of the explanans of Darwinian explanations. Whereas differential rates of reproduction within a population are straightforward to define theoretically, their causes and specific shape might vary widely. Darwin described a number of specific examples of a change of traits and their relative selective advantages, but these examples offer little in terms of generalisation. The shape and dynamics of the selectively relevant environmental factors over the relevant timespan might be different in each case, as might the time-span that will need to be considered the relevant frame

of reference (see, e.g., the arguments between punctualists and gradualists, cf. Eldredge, Gould [49] versus Dawkins [50]).

To sum up the historical situation, evolutionary theory, at the time of Turing's writing, was in such a shape that the factors potentially responsible for natural selection were difficult to identify or quantify. It was hard to list and take measurements of potential, partly unobserved environmental factors that would have acted on different stages of an evolving population and thereby accounted for an individual population member's overall form. Mendelian genetics provided a developed statistical framework of explanation, but the structure of genes and the functions of genetic mechanisms were fully established only by Watson and Crick in 1953 [51], thus shortly after the publication of Turing's 1952 paper. While molecular genetics would leave Turing's morphogenetic model intact and actually support it, it had a major effect on evolutionary modelling, affecting the definitions of the units of heredity and the units and levels of selection [52–55]. Therefore, up until and partly even beyond the mid-20th century, it would remain harder to adequately and precisely formulate both explanandum and explanans in evolutionary than in morphogenetic modelling. However, near the time of the Second World War, the 'modern synthesis' in evolutionary theory, which combined Darwinian selection with Fisher–Haldane–Wright's mathematical population genetics [9–11], and which was paradigmatically stated by Julian Huxley [56], offered more precise definitions of explanans and explanandum and was in the process of becoming the dominant paradigm in biological theory. It still had to compete with the various vitalist approaches that Thompson and Turing rejected, too, and it still faced a strong challenge from Thompson and the organicists, which it survived, ultimately side-lining organicist and vitalist positions for many years.

Given the state of the art in evolutionary theory and genetics at the time, Turing might have made the methodological choice of resorting to some kind of analogous simulation modelling of evolutionary processes that involved invented organisms reproducing in invented environments. This is what John von Neumann [57] proposed with his cellular automata. However, in this case it is the modeller who designs all the objects and processes under investigation, with an expectation that their behaviour generalises to natural systems in natural environments to some extent. In contrast, Turing's aim was to devise models that directly refer to and explain phenomena in the real world. Abstracting from the concrete biochemical realisation of morphogenesis in the way that Turing did is not damaging to his theory, as his equations still demonstrably match organic patterns and their formation processes. Such an abstractive, purposefully 'black box' approach is not equally applicable to Darwinian evolutionary explanations because without some knowledge of population genetics—and to some extent also molecular genetics—it remains powerless with respect to explaining central aspects of its phenomena: how do gene frequencies change in a population over time? What environmental factors might drive that change? How could genetic change account for the apparent design of traits? These were questions that the modern synthesis began to answer and that modern genetics was able to more comprehensively address. Leaving these aspects in a black box in the way that pre-synthesis Darwinian theory did was detrimental to its standing vis-à-vis a mathematically precise and explanatory theory of organic development.

The accessibility of morphogenesis to mathematical modelling was confirmed by Turing as one of the motives for him to work on a "mathematical theory of embryology" (see above quote from [38]). This does not directly explain his choice to work on morphogenetic explanations but rather suggests he had waited for a possibility to practically implement the choice that he made on other grounds until it became practically feasible. The feasibility was directly related to the availability of the Ferranti Mark I computer: "Our new machine is to start arriving on Monday [12 February 1951]. I am hoping as one of the first jobs to do something about 'chemical embryology'. In particular I think one can account for the appearance of Fibonacci numbers in connection with fir-cones." [3].

So, although Turing's theory of morphogenesis was not computational in the straightforward sense of being an application of his computational method (see Section 2.1 above),

and although it was also mathematically distinct from his work on computation as it relied on continuous rather than discrete functions, he expected his morphogenetic models to be partly implementable in digital computers by means of discrete approximations to those continuous functions. However, it does not seem that he accomplished such an implementation at the time, nor did he expect to make a digital computer actually solve the equations. Instead, he started to conduct some computer simulations in a more experimental fashion (Hodges [6], pp. 600, 662). Judging from the observations in Swinton [58], it seems that Turing only got as far as making a computer generate numerical patterns from differential equations that he had already solved in mostly manual fashion. These difficulties aside, key aspects of explanandum and explanans were empirically or conceptually accessible in such a way as to be given a mathematical formulation, which was not and partly still is not the case for Darwinian theory of evolution. There are no successful mathematical models that would comprise key concepts and mechanisms of Darwinian evolution and were able to model the development of an evolutionary lineage *par excellence* [59].

Apart from the issue of the varying degrees of accessibility to mathematical modelling, it might seem striking that Thompson's and Turing's theories on the one hand and Darwin's on the other could be perceived as competitors for the explanation of the same set of phenomena. *Prima facie*, they seem to address distinct phenomena on distinct levels. As we have seen, Darwinian theory, at least in its original variety and up to the establishment of gene-centric theories of selection [52,60], was in principle concerned with populations—and how populations turn into distinct species. In contrast, Thompson's theory, and Turing's along with it, were concerned with organic patterns on the individual level—and how they come to grow into a certain shape. Natural selection might work on individuals in terms of diminishing versus enhancing their reproductive chances but all relevant effects manifest on the population level and need to be spelled out in terms of adaptive functions. Morphogenesis cares about populations only as aggregates of individuals. Neither populations nor adaptive functions have explanatory relevance to morphogenetic processes. Likewise, natural selection focuses on one stage of the development of an individual, namely its reproductive age, whereas theories of organic form concern all stages of development. As already indicated in Section 3.1, Turing's theory would focus on the incipient stages, while Thompson's was concerned with later developmental stages of an individual organism.

Hence, taken at face value, morphogenesis and Darwinian evolution seem to be distinct theories adapted to distinct subject areas. However, to the extent that Darwinian theory seeks to explain the apparent design of organisms by reference to what happens within populations and during the reproductive age of organisms, and to the extent that Thompson explicitly denied that Darwinian theory could provide an explanation of design, such a neat separation does not seem possible. In the end, leaving aside the methodological and theoretical differences, both theories were meant to answer the same substantive question from different perspectives, quarrelling over the same turf despite all their differences in approach: why some definite and apparently goal-directed morphological patterns occur and reoccur in organisms.

3.3. *Explicit Theoretical Reasons*

Apart from the previous considerations that all concern general theoretical presuppositions that were not discussed by Turing himself, he provided two explicit justifications for devising the specific type of explanation embodied in his theory of morphogenesis. Both justifications refer to the aforementioned issue of accessibility of proper explanatory categories and can be considered aspects of those more general issues. We will briefly address these before discussing a significant but implicit tension that remains within the approach thus vindicated.

First, Turing referred to the apparent lack in Darwinian theory of an unambiguous explanation of the fact of the omnipresence of certain patterns of organic form across separate taxa. This was a knowledge gap that would be difficult to fill for Darwinian

theory because its aim is to explain differentiations of morphological patterns rather than underlying uniformities: how and why some morphological structure came to exist as a trait that provides an adaptive response to specific environmental conditions. Its aim was not to explain the existence of ubiquitous homologies of traits under virtually all environmental conditions and across distant taxa but to explain how existing homologies among related taxa come to be shaped towards distinct functions. At the same time, an explanation of how those homologies arise in the first place could be accomplished by reference to universal biochemical and biophysical processes. It will be useful to quote at some length what Turing said on this topic in his joint work with Wardlaw:

One major result of the comparative morphological studies of the post-Darwinian period, and also of the contemporary period of renewed interest in morphogenesis, has been an appreciation of the fact that similar morphological and anatomical features may be found in organisms of quite distinct taxonomic affinity. These homoplastic developments, which have resulted from parallel or convergent evolution, have also been aptly described as constituting homologies of organisation and are of general occurrence in the Plant Kingdom. [. . .] This being so, the factors which determine these kinds of pattern, or homologies of organisation, should be ascertained and closely investigated [. . .] The contemporary explanation of comparable or homogenous developments in related organisms is that there are genes, or groups of genes, which are common to the organisms, and that these control or determine the observed developments**. But where similar features are present in unrelated organisms, the comparable developments cannot be attributed to common groups of genes. In attempting to explain the phenomenon of homology of organisation two possibilities may be entertained:

- (i) comparable morphological features appear because essentially the same kind of process is operating in each of the non-related organisms; or
- (ii) that essentially different processes may, nevertheless, yield comparable morphological results.

On grounds of probability, the first explanation seems preferable to the second, but, because of the very great diversity of living organisms the second cannot, and should not, be eliminated out of hand. Whether we are concerned with developments which are considered to be more or less directly gene controlled, or with homologies of organisation, in which the importance of specific genetic factors has yet to be ascertained, the visible phenomena of morphogenesis have their inception in biochemical and biophysical reaction systems. ([30], pp. 38–39)

These two distinct possibilities can be kept open in Turing's theory precisely because of his substrate neutrality postulate. Whether 'biophysical reaction systems' in different taxa are identical, closely related or significantly distinct on the level of biophysical realisation is irrelevant both to the resulting morphological structure and to the general operational principles of biophysical reaction systems. If biophysically distinct systems give rise to morphologically similar structures (as in (ii) above), the generality of Turing's morphogenetic principles is vindicated. If an essentially identical kind of process operates in taxonomically distant species (as in (i) above), Turing's principles are vindicated, too.

Turing's second explicit justification for his approach is his statement, reportedly made to his PhD Student Robin O. Gandy, that by his morphogenetic theory he intended to "defeat the argument from design" ([6], p. 543), which means to refute any theories of organic development that refer to or implicitly presuppose higher-order forces or laws of nature that are specific to animate nature. This intention resurfaces in a more carefully worded statement in Turing's work with Wardlaw:

Unless we adopt vitalistic and teleological conceptions of living organisms, or make extensive use of the plea that there are important physical laws as yet undiscovered relating to the activities of organic molecules, we must envisage a

living organism as a special kind of system to which the general laws of physics and chemistry apply. ([30], p. 45)

This programmatic statement can be seen not only as a commitment to exclusively refer to physico-chemical laws in explaining the development of organic forms, and it is not only an explicit rejection of vitalism, but it also provides a reason for not working within a Darwinian framework. To many of Turing's contemporaries, again including Thompson, pre-synthesis Darwinian theory appeared to be burdened by residual teleological conceptions that paper over the problem of how biological organisation first arises (Thompson [2], pp. 5–6, 888–890). Natural selection's contribution to evolution should not be the provision of design by proxy of producing adapted traits but should instead be considered purely negative: "to weed, to prune, to cut down and to cast into the fire" un-fit variants ([2], p. 270). While Darwinian theory leaves the origin of biological organisation open—Darwin himself admitted for the possibility of a higher-order act of creation in the closing passage of *The Origin of Species* ([61], p. 490)—not even a general purpose of survival and reproduction needs to be presupposed *per se* by Turing's theory. Physico-chemical laws will do.

4. Discussion: The Limits of Mechanism and the Metaphysics of Life and Mind

With these considerations concerning Turing's influences and methodological premisses in mind, one thing remains unexplicated both by Turing himself and by the secondary sources that we have been discussing: There is a tension between his mechanistic style of explanation and his project of contributing to an otherwise organicist research programme. One way of resolving this tension will be to consider them two sides of the same coin: Turing used a set of mechanistic explanations to constructively address the most critical spot of the organicist edifice: the incipience of biological form on the most basic level. In a Darwinian framework, which is vocally committed to mechanistic explanations, the identification of some such basic mechanisms would be the expected solution, but as we saw, they were not available to any useful degree of sophistication and rigour at the time of Turing's writing and still remain difficult to attain. In an organicist framework though, mechanistic explanations might seem unexpected or even out of place and working against the spirit of that framework. However, while Turing adopted his research problem from the organicist framework, he never explicitly subscribed to it or confined himself to working within it. Instead, he committed himself to a mechanistic programme of explanation, but even then, he did so only to a certain, significant but expressly limited, extent while never concerning himself with the research problems of Darwinian theory and its own variety of mechanistic explanation.

To understand what is at issue here, it will be useful to consider organicism and mechanism on two levels: paradigms of scientific explanation and metaphysical doctrines. To make this distinction clear, we will first outline the relation between Turing's mechanism and a more general notion of mechanism: In Turing, mechanisms are an abstract, formal category applied to logico-mathematical problems that are solvable by an 'effective procedure', as briefly outlined in Section 2.1. Turing's notion of a deterministic, mechanical procedure of solving logico-mathematical problems can be read as building on a classical *naturphilosophical* conception of mechanism, as Webb [62] does: In addressing the Gödelian question whether there can be a finite system that is capable of determining the provability of a sentence in some calculus, Turing provided an indirect route to answering the metaphysically mechanist question in modern philosophy whether all phenomena in nature must be considered consequences of a finite set of deterministic laws, in analogy to the operations of a machine. His answer to the first question was negative, in that Turing demonstrated that there is no such finite procedure for solving the decision problem, but in doing so, he demonstrated that there is a relevant domain of mathematical problems and empirical phenomena on the near side of Gödel's decision problem that in fact *are* amenable to solutions by means of effective, mechanical procedures.

The concept of mechanism has experienced a related-but-different career in philosophy of science, where it characterises a certain general type of scientific explanation and its

epistemic norms, of which Turing's approach to computation has been mobilised as the paradigm. It is not necessarily accompanied by a matching set of metaphysical convictions, under which nature is likened to the workings of some sort of machine. In an essay that discusses the distinctions between mechanist, organicist and vitalist approaches in modern biology, Garland Allen highlights that:

Mechanists have tended to hold to some kind of reductionist strategy, that is, the belief that to understand higher level processes it is necessary to investigate them at lower levels of organization: for example, cells in terms of molecules, organs in terms of cells, organisms in terms of organ-system. ([63], p. 266)

Mechanists seek to identify, from a top-down perspective, how these components relate to, and produce, the overall complexity of a system. More generally, according to a standard definition of the "New Mechanism" in philosophy of science by William Bechtel and Adele Abrahamsen, "A mechanism is a structure performing a function in virtue of its component parts, component operations, and their organization. The orchestrated functioning of the mechanism is responsible for one or more phenomena" ([29], p. 423). Although some prominent New Mechanists, such as Carl Craver [64], object to a characterisation of the programme as reductionist, mechanism can be considered a reductionist strategy to the extent it proceeds from explanations of a structure's component parts and considers an account of their coordinated activity sufficient for an explanation of the overall structure's properties and behaviour, therefore neither requiring inherent nor extraneous factors to accomplish that explanation.

One counterpart to the mechanistic paradigm is organicism ([63], p. 279). It is based on the belief that complex phenomena have to be cognitively grasped as a whole in order to be properly understood because a consideration of all the various levels of organisation of the system under investigation and their interrelations is crucially important to an explanation of its overall properties and behaviour. Unlike in vitalism, however, complex organic structures are, first, considered the result of a self-organising process of pattern formation rather than pre-determined by some inherent teleological principle. Second, organic structures are distinguished from non-living matter by their capacity of continuous self-regulation rather than by the presence of some kind of life-force. While being on the same page as organicism in their rejection of the metaphysical underpinnings of vitalism, the reductionist character of mechanistic explanations would fail to grasp the principles of pattern formation and self-regulation, as these always and by necessity require a macro-level perspective on the entire organism. Such a perspective is required because some of its properties might either be extraneous to the properties and behaviours of its component parts or emerge from their interactions, without allowing for an explanatory reduction to the properties and interactions of these parts. For example, Thompson's geometric transformations of organic shapes always affect the organism or larger substructures as a whole. They cannot be identified on the elementary level. The transformations in question are caused by environmental stimuli or inherent developmental constraints on the organism, which might work in conjunction. Although primarily intended as a hypothesis concerning explanations in biology, organicism would still associate or be associated with metaphysical principles of wholeness and complexity ([63], p. 280).

In turn, the mechanistic approach relies on a notion of cognitive accessibility of both explanandum and explanans:

[The mechanistic programme] provided a way in which biology could dissociate itself from the earlier tradition of natural history that focused too much on descriptive methods and speculative theories such as reconstructing evolutionary histories of various taxa. True science [. . .] looked not at hypothetical historical causes but at immediate proximate causes in terms of the material, knowable components of the process order [sic!] investigation. This was, of course, the model of true science exemplified by physics and chemistry. ([63], p. 280)

Still, the mechanistic programme can be parsed into two related-but-distinct and sometimes conflated positions, one concerning methods and norms of explanation in science and one more philosophical and metaphysical, under which organisms and other biological systems would be not merely explained in terms of but substantially likened to the interactions of the material components of a machine ([63], p. 263).

To the extent that Turing's concept of mechanism is a special case of mechanism about explanations, his theory of morphogenesis, just as his theory of computability and his proto-connectionist models, are members of the same family. There are important aspects and domains of life and mind that can be explained in this fashion. However, this does not amount to a verdict on whether Turing also adhered to metaphysical mechanism. This would be the default assumption of any adherent of strong artificial intelligence or pancomputationalism, according to which "computation is cognition" [65] or, respectively, every sufficiently complex open physical system implements every computational process ([66], Appendix). If all aspects of life and mind can be explained in mechanistic fashion, there is no need to assume that these phenomena *cannot* be modelled by machines on the physical level and likened to the elements of machines and their interactions on a metaphysical level. This assumption does not hold true for Turing's views about life and mind. Possibly, not all aspects and domains of life and mind can be explained in a mechanistic fashion, even though morphogenetic processes and neural information processing can. If Turing's notion of mechanism in computation holds, every problem that is amenable to a determinate solution at all can be solved by a deterministic, mechanical procedure. This does not amount to the claim that *any* problem whatsoever can be solved in the same fashion. Turing's mechanistic account of computation was never supposed to cover problems outside the domains amenable to effective or 'mechanical' procedures of calculation. Therefore, some of the aspects and domains of life and mind might not permit being likened to the interactions of the material components of a machine because they *are* not like the interactions of the material components of a machine.

Turing never provided a systematic account of the non-mechanical aspects of life and mind, nor did he try to prove their existence. What he did is admit for their possibility and provide some partly disparate indications: Most immediately related to his morphogenetic model, Turing never explicates the presumed nature of the random or quasi-random factors that initiate a morphogenetic system's departure from a stationary state. Their role in the model is that of extraneous factors that may remain unexplicated without undermining the validity of the model. However, they thereby remain outside the domain of the mechanistic explanation in question. They might either be amenable to a mechanistic explanation of their own—which would make them quasi-random in ignorance of these specific explanations—or they might be genuinely random effects or, in principle at least, the work of higher-order forces. Turing's model was neither able nor supposed to distinguish between these three possibilities. He thereby left open the possibility not merely of the importance of other, yet-to-be explained mechanisms but also of non-mechanistic aspects and domains of nature in a metaphysical sense.

In terms of more concretely admitting the possibility non-mechanistic aspects and domains of nature, there is a report on a conversation during Turing's Bletchley Park days in 1941:

Once Alan produced a fir cone from his pocket, on which the Fibonacci numbers could be traced rather clearly, but the same idea could also be taken to apply to the florets of the daisy flower. In this case it was rather harder to see how to count off the petals, and Joan wondered whether the numbers did not then arise merely as a consequence of the method of following them. This was pretty much the view of D'Arcy Thompson, who played down the idea that the numbers had any real significance in nature. They made a series of diagrams to test this hypothesis which did not satisfy Alan, who continued to think about 'watching the daisies grow'. ([6], pp. 261–262)

Although no conclusion is stated here, Turing appears to have been considering the possibility of a real significance of numbers in nature, in departure from Thompson's view. In that case, he would have either held or taken seriously a belief in the actual mathematicity of the world: mathematical objects, such as numbers, are not just conceptual instruments for the purpose of describing the world, but are 'embedded' in the world, including in animate nature. There would be mathematical properties of organisms that *might* be traced by a mechanistic model as that devised by Turing [1] and that *might* be amenable to computer modelling, but the presence and nature of these mathematical properties itself would not be explained by that mechanistic model. Nor would it become transparent by means of a mechanistic explanation whether there is a necessity or purpose to those mathematical properties of nature, or whether they are a mathematical-ontological scaffolding whose manifestations merely reflect the way the world happens to exist.

The most explicit admission of non-mechanistic aspects and domains of nature and their importance can be found in Turing's early meta-mathematical work. If we follow his 1939 "Systems of Logic Based on Ordinals" [67], where he explores the properties of his mechanical procedures for solving logico-mathematical problems, Turing tentatively but unequivocally points beyond the domain of mechanistic explanations. In that work, he emphasised the role of intuition in mathematical reasoning:

In consequence of the impossibility of finding a formal logic which wholly eliminates the necessity of using intuition, we naturally turn to 'non-constructive' systems of logic with which not all the steps in a proof are mechanical, some being intuitive. ([67], p. 216)

Turing likened the role of intuition in mathematics to an 'oracle' that provides 'some unspecified means of solving number-theoretic problems' ([67], p. 172). He added that the oracle is certainly not a machine, that is, it is not something that could provide for mechanical solutions of whatever idiosyncratic kind to number-theoretic problems. However, Turing envisioned the principled but unspecified possibility of connecting the oracle to a deterministic computing machine, resulting in a machine paired with a non-mechanical component that might provide solutions to uncomputable logico-mathematical problems. He gave no indication how this combined system might operate, leaving later scholars to debate whether a Turing Machine paired with an oracle should itself be considered a machine (see Copeland and Proudfoot [68] pro and Hodges [69] contra).

There are also some more scattered and less systematically pertinent pieces of evidence for the limitation of mechanism in Turing's work. In a short unpublished essay that he probably wrote in 1932 as a young Cambridge student ("Nature of Spirit", quoted in full length in Hodges [6], pp. 82-83), he entertains a thought inspired by quantum theory: Knowledge of states of the physical world at the most elementary, that is, the atomic level "must break down on the small scale", where there is no physical determinism but rather a "combination of chances" and possibly some determination caused by human "spirit" that can interact with elements of the universe. This is a metaphysical interpretation of the Schrödinger problem, where only observation will determine the state of a particle. Elementary particles, despite being thus subjected to random processes and some un-explicated and possibly inexplicable factors, were at the same time governed by some higher-level, more deterministic laws that can be mathematically expressed. Even more cryptically, Turing [47] discusses an objection to the possibility of thinking machines from 'Extra-Sensory Perception', which he considers strong and fact-based ("Unfortunately the evidence, at least for telepathy, is overwhelming.", [47], p. 453).

None of these observations would imply or insinuate that, while Turing was a mechanist about explanations within certain domains, he was an organicist on a metaphysical level. As elegant as this solution might look, there is no evidence on the one hand that Turing harboured a holist conception of the organism as it would be characteristic of an organicist metaphysics. There is no reference to an inherent complexity or to emergent properties of organisms as complex systems that is characteristic of organicism and would become a trademark of cybernetic reasoning. On the other hand, the evidence for a non-

mechanist metaphysics in Turing that we collected is too scattered and heterogeneous to allow firm conclusions concerning a systematic set of metaphysical beliefs. However, our evidence supports the conclusion that Turing considered the domain of mechanistic explanations complete and self-sufficient to the extent that every phenomenon within that domain can be mechanistically explained, but that he was prepared to accept the existence of domains of life and mind that might be connected to the former domain but that lie beyond the reach of those explanations. As far as our evidence is concerned, these non-mechanistic domains in fact look less similar to what an organicist metaphysics would suggest than to a notion of essentially arcane qualities of reality that provide it with purpose and direction in ways that likening life and mind to the operation of the components of machines of any kind could not. Under this interpretation, vitalist philosophers of nature would be more probable than either mechanists or organicists to find something familiar and likeable in Turing's metaphysical views, as sketchy as they may have remained.

5. Concluding Remarks

On the preceding pages, we have sought to sketch an image of the philosophical relevance of Turing's work that goes beyond the standard accounts of his contributions to metamathematics, computer science and artificial intelligence. Starting from a reconstruction of the part of this work that is seemingly farthest removed from his computational inquiries and the specific type of mechanistic reasoning that Turing himself helped to establish, we have demonstrated, first, that his biological inquiries, despite their organicist background, were not extraneous or exotic to the main body of his work. Second, we have traced some of the influences that shaped his specific biological interests. Third, we have made some suggestions as to how and to what extent his work on developmental biology actually ties in with his concept of computational mechanism. In fact, a grasp of Turing's biological thinking might ultimately help to get a clearer view of the nature and scope of that concept, including the power and the limits of mechanism as a more general philosophical idea.

Let us briefly indicate two potentially fruitful lines of further research along the lines we indicated here. On the historical and biographical side, it will be worthwhile to pin down when exactly and, if applicable, through whom Turing came to read Thompson's *On Growth and Form*. Many authors identify this work as a key intellectual influence on Turing, but few of them even try to trace the route that this influence has taken, which would not seem to come naturally to a young Turing more interested in chemistry and physics—and in biology only in the incarnation of Brewster's mechanistically minded science for children.

On the more systematic side, it will be interesting to explore a line of inquiry that Turing could only begin to think about before his untimely death: How could his morphogenetic theory be applied to the anatomy of the brain? Turing was confident that this would be possible: "The brain structure has to be one which can be achieved by the genetical embryological mechanism, and I hope that this theory that I am now working on may make clearer what restrictions this really implies." [38]. If successful, such a model of the brain might have connected to his proto-connectionist inquiries and provided them with some biological grounding on the one hand and with a path to explanations of higher cognitive functions on the other. It does not seem self-evident though that the general morphogenetical model would scale to the level of complexity implied by the anatomy of the brain. Finding out whether it does would be a test of the explanatory reach of a Turing-style mechanistic model—or whether a genuinely organicist explanatory approach would be required.

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Notes

- ¹ When using u and v as placeholders here, we are purposefully departing from Turing's own notation because it is not consistent in his morphogenetic works. At the same instance, we follow his intuition not to distinguish between the substances and their concentration rates in notational terms. Since the concentration rates of the substances and the dynamics between them are what matters, a separate notation for the substances seems unnecessary from an ontological viewpoint.
- ² A steady (stationary) state of a variable means that it does not change over time, whereas stability means that under conditions of minor perturbations, it will converge back to its initial steady state value.

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