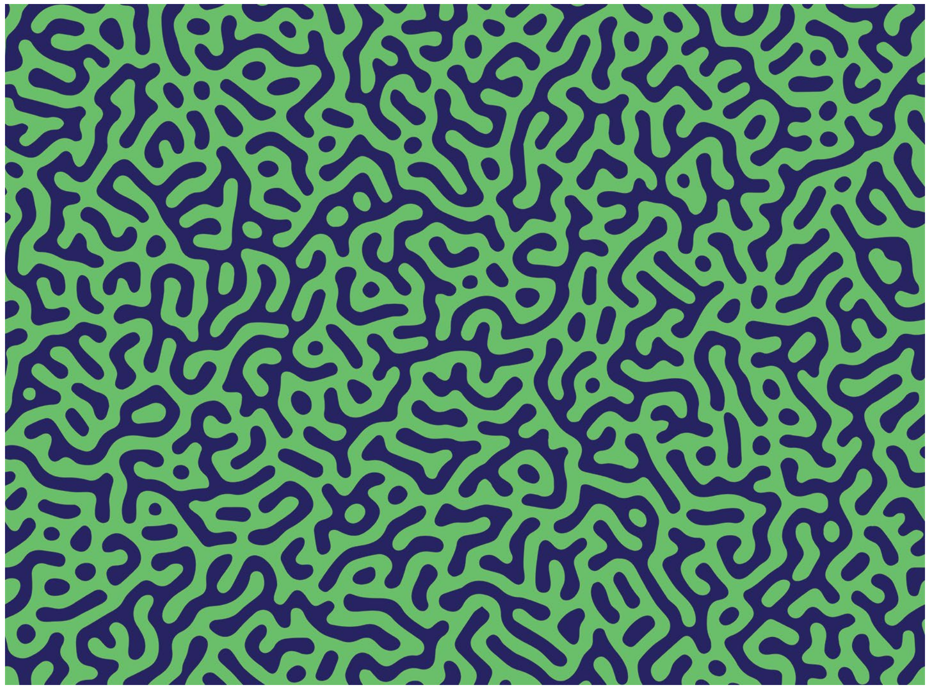
Turing patterns, 70 years later

On the 70th anniversary of Alan Turing's seminal paper on morphogenesis, we look back at the history of the paper and its many applications.



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Alan Turing, often regarded as one of the fathers of modern computing, has been widely recognized for his contributions in the field of computer science. Notably, Turing developed the Turing machine, a hypothetical machine that manipulates symbols on an infinite and one-dimensional tape according to a table of rules. A Turing machine can simulate any computer algorithm and provided the mathematical formulation for today's digital computers. During a lecture in 1947, Turing hinted at the concept of computer intelligence — likely one of the first mentions of this concept — by stating that "what we want is a machine that can learn from experience" and further clarifying that "the possibility of letting the machine alter its own instructions provides the mechanism for this"[1]. Turing eventually proposed what is known as the Turing test, a method for determining whether a machine can demonstrate human intelligence, which has been highly influential and the subject of much discourse in the field of artificial intelligence.

Perhaps less well-known, although equally remarkable, are Turing's contributions in the field of mathematical biology. On 14 August 1952, Turing published his only research paper in the field of biology titled 'The chemical basis of morphogenesis'[2], in which he proposed a mechanism to explain the patterns observed in nature. More specifically, Turing noted that a unique property of biological systems is asymmetry, which cannot arise solely due to physical laws. Taking the development of an embryo as an example, he stated that an embryo begins as a symmetrical mass of cells and that the laws of physics could not explain, in most cases, the development of organs such as limbs and eyes at precise locations. Instead, he proposed that the development of asymmetry in biological systems could arise as a result of signaling molecules that emerge from a certain source in the tissue and move away from their source, leading to a concentration gradient and patterns within a system. Turing termed these signaling molecules as morphogens. However, any patterns arising in a system of molecules moving according to the basic laws of physics would eventually vanish, leaving behind no observable patterns: there would need to be a process that would generate and amplify patterns in the system in a stable manner. To explain the development of patterns, Turing proposed the addition of instability to a linear system of molecular movement by introducing diffusion of morphogens at specific time points. Based on theoretical calculations, the addition of diffusion led to the destabilization of the system and the development of patterns, which are now referred to as Turing patterns. While the development of patterns due to the introduction of diffusion seemed counterintuitive at the time, this is now a widely accepted system known as the reaction–diffusion system.

Turing's study was a landmark one for a couple of reasons. First, the study introduced the concept of morphogens and reaction–diffusion systems, which have substantially impacted not only the field of developmental biology, but also various other fields, including chemistry, physics and ecology. In addition, the study has influenced the field of mathematical biology to a great extent given its unique use of numerical analysis to study biologically observed phenomena.

Interestingly, Turing's work on morphogenesis remained largely unknown until more than 25 years later, when researchers pointed to the existence of morphogen gradients[3]. Nüsslein–Volhard and Wieschaus showed that mutations at 15 loci in a *Drosophila* melanogaster disrupted the segmental pattern of the larva, and that these mutations had three distinct levels of spatial organization. Ultimately, the results indicated that a morphological gradient was responsible for the segmental pattern formation in the system. The experimental confirmation of the Turing patterns came even later, in 2014, when researchers were able to reproduce them in chemical cells[4].

But as indicated above, the applications of Turing patterns are not just seen in developmental biology — or biology in general. To name a few, Turing patterns have explained the shell structure and patterns observed in aquatic mollusks[5], and they have also been used to gain insights into human settlement[6] and to design water filters[7]. Experimentally, Turing patterns have been able to explain the spaced transverse ridges of the palate in mammals[8]. In 2021, researchers showed that a strained atomic bismuth monolayer on the surface of niobium diselenide displays Turing patterns[9], an observation that may play a crucial part in the development of microdevices. Fascinatingly, artists have also used Turing patterns to create generative art.

Today, 14 August 2022, the manuscript 'The chemical basis of morphogenesis' completes 70 years. Sadly, Turing passed away two years after its publication and was not able to see the broad implications of his study. And from the looks of it, we have barely begun to scratch the surface of the potential applications of Turing patterns. ❒

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