Afterword:

1952: Alan Turing and Morphogenesis

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I often drive right over a memorial to Alan Turing. A section of the Manchester ring-road is named in his honour, and that – together with a pigeon-spattered statue by the University – is all that commemorates the existence of one of the city's most influential figures. His death in 1954 came at the end of a sustained period of persecution by the authorities.

It's been said that Turing contributed more to the defeat of the Nazis than Eisenhower. Certainly, it's believed that his contribution to cracking the German Enigma code system was a decisive point in the war. Yet, as Jack Good, a contemporary of Turing's pithily observed, 'It was a good thing that the authorities hadn't known Turing was a homosexual during the war, because, if they had, they would have fired him – and we would have lost.'

Although Turing is best known for breaking the German codes, and thus helping to bring the war to a close, he is also celebrated for his seminal work on the nature of computation, and non-specialists might even recognize his eponymous Test – the method for evaluating whether a computer can truly be 'intelligent', by engaging it in conversation. Yet few will know of his contribution to the study of the natural world, which Jane Rogers describes so eloquently.

The modern world is a dense network of interactions, both embodied and virtual. Connections are everything, yet Turing was profoundly disconnected from the world. We know very little about his thoughts on human events, yet it is clear that he yearned for connection – to the universe, to his dead childhood friend and first love, and to the deep, deep patterns of nature.

Turing's connections were intellectual, and spanned several disciplines. In the modern era, when 'inter-disciplinary' science is almost de rigueur, we take such thinking for granted. Yet, in his time, Turing was one of the very few pioneers who could see the commonalities between seemingly disjoint areas.

He grounded mathematical logic in the physical world of engineering, with the creation of what would become known as the 'Turing Machine'. By defining the notion of a computation, as well as the limitations on what computers could achieve, he laid the foundations for modern computer science and gave it a rigorous framework.

Later on, he would be captivated by the idea of artificial intelligence, and defined the criteria by which a machine (or computer program) could reasonably be called 'intelligent'. His motivation was clear when he explained, in 1951, that 'The whole thinking process is still rather mysterious to us, but I believe that the attempt to make a thinking machine will help us greatly in finding out how we think ourselves.'

In his childhood, Turing was fascinated by nature, inspired by a copy of *Brewster's Natural Wonders Every Child Should Know*. His experiments were in chemistry, not mathematics. Towards the end of his life, he focussed on the problem of morphogenesis. How can a single fertilized cell grow and develop into a fully-fledged organism? What processes can take such a tiny seed and convert it into an animal? Or, as Ian Stewart puts it, 'How do you cram an elephant into a cell?'[1]

In 1952, when Turing published his seminal paper 'The Chemical Basis of Morphogenesis'[2], Watson and Crick were still a year away from publishing their structure of DNA. Yet it was clear, even then, that the body was somehow an emergent form. Turing was inspired by the Fibonacci sequence observed in many plant structures (for example, the branching of trees, or the arrangement of a pine cone). He wanted to know how complex biological growth and development could be achieved via simple, natural mechanisms.

Of particular interest to Turing were the patterns observed in animal markings. He sought a scientific explanation to Kipling's question of how the leopard got his spots. Stripy zebras and spotty cows; each presented the same mystery. Turing started from the assumption that markings were laid down in the developing animal as an embryonic pre-pattern, or a 'template'. Over time, as it grew, this template would be 'filled out' by pigment on the embryo's surface (that is, the skin). Colour by numbers.

Turing therefore set out to understand precisely how this pre-pattern could be sketched out using chemicals. He imagined two different processes working together: reaction and diffusion. He coined the term morphogen ('generators of form') to refer to chemicals which could react together to make other molecules, and which could somehow influence tissue development. These morphogens and their products could also 'spread', or diffuse, across the embryonic surface, and whether or not a particular skin cell produced pigment depended on the relative level of morphogen in the cell.

Within such a system, Turing proposed the existence of two substances, one a catalyst (or 'activator') that stimulates the production of both chemicals, and the other an inhibitor, where the latter slows production of the former. The concentrations of each chemical can oscillate between 'high' and 'low' as the chemicals spread over the surface, giving rise to complex patterns (corresponding to the pre-pattern) if the inhibitor diffuses much faster than the activator.

By bringing to bear a combination of analysis and computer modelling on problems in the natural world, Turing pioneered the study of computational biology. His morphogenesis work was largely ignored by experimental biologists, though, who argued that his model was founded on a number of untested hypotheses. Very soon, however, evidence for the existence of natural 'Turing patterns' came in the form of the BZ reaction (named after its co-discoverers, Belousov and Zhabotinsky). This reaction proved that, by mixing a handful of specific chemicals, one could spontaneously obtain rings, spirals, spots, and other patterns – in a dish. Even then, observers were sceptical, pointing out that BZ patterns moved across the dish, unlike the static markings on animals. When the experiments were later repeated in gels, the patterns became more 'realistic', but by this time, as Ian Stewart explains, 'biologists had lost interest in the debate',[3] and Turing was long dead[4]. Recent work in fish, chicks and mice has leant increasing support to the relevance of Turing's model[5], but its real power lay in the demonstration of how order could arise spontaneously from disorder. It suggested an entirely new approach to the understanding of living systems.

Turing's contributions (both scientific and historical) will endure forever, and his vision lives on in a diverse range of research fields, from artificial intelligence to self-organization and chaos theory. As his biographer[6], Andrew Hodges explains, Turing's philosophy '...depends upon a synthesis of vision running against the grain of an intellectual world split into many verbal or mathematical or technical specialisms. He preached the computable but never lost natural wonder; the law killed and the spirit gave life.'[7]

1. Ian Stewart, *Mathematics of Life*, p. 198. Profile Books (2011).
2. A. M. Turing, 'The Chemical Basis of Morphogenesis'. *Phil. Trans. Roy. Soc.* London B, 237:641 (August 1952), pp. 37-72.
3. Ian Stewart, *Mathematical Recreations*. Scientific American (November 2000).
4. The story of the BZ reaction and its sceptical reception by the scientific community would be a good subject in its own right. Belousov was so disheartened by resistance to his discovery that he effectively withdrew from science. See A. T. Winfree, 'The Prehistory of the Belousov-Zhabotinsky Oscillator'. *Journal of Chemical Education* 61:8, p. 661-663 (August 1984).
5. S. Kondo and T. Miura, 'Reaction-diffusion Model as a Framework for Understanding Biological Pattern Formation'. *Science* 329, p. 267-275 (2010).
6. Andrew Hodges, *Alan Turing: The Enigma* (Vintage, 1992).
7. Andrew Hodges, *Turing* (Great Philosophers series, Phoenix, 1997).