Alan Turing

HIS WORK AND IMPACT

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Nicholas Gessler connects past and future —

THE COMPUTERMAN, THE CRYPTOGRAPHER AND THE PHYSICIST

> The field of cryptography will perhaps be the most rewarding. There is a remarkably close parallel between the problems of the physicist and those of the cryptographer. The system on which a message is enciphered corresponds to the laws of the universe, the intercepted messages to the evidence available, the keys for a day or a message to important constants which have to be determined. The correspondence is very close but the subject matter of cryptography is very easily dealt with by discrete machinery, physics not so easily. (Turing, *Intelligent Machinery*, p. 509 above)

We recall the past because it serves the present. Today, it gives us fresh insights into ideas that we may have overlooked, and it calls our attention to ideas that others may have missed in prior days. It offers us new perspectives, larger vistas on a target of inquiry from points of view separated by space, time, culture and preconception. Since those targets arose in contexts that were so different than today's, we can open past ideas to a larger audience. We open a dialog with yesteryears, an exploration that challenges our understanding of the past and present that make us question whether progress has been made, why or why not, and how. With humility, we reassess our own work in the light of those that have come before us. With conceit, we enlist our antecedents as advocates for our own agendas. We engage to give our present projects richer meaning. What then, are we to make of Turing's statement? What are the implications that arise from what we take Turing to mean?

1. Science as cryptanalysis

> [Newton's}experiments were always, I suspect, a means, not of discovery, but always of verifying what he knew already ... He looked on the whole universe and all that is in it *as a riddle*, as a secret which could be read by applying pure thought to certain evidence, certain mystic clues which God had laid about the world to allow a sort of philosopher's treasure hunt to the esoteric brotherhood ... He regarded the Universe as a cryptogram set by the Almighty—just as he himself wrapt the discovery of the calculus in a cryptogram when he communicated with Leibniz. By pure thought, by concentration of mind, the riddle, he believed, would be revealed to the initiate. (Keynes, pp. 313–314)

My first, probably superficial, interpretation of his claim was as a metaphor, an analogy, between the practice we now call cryptology (the study of codes and ciphers), or more specifically cryptanalysis (the breaking of encrypted communications), and the practices of science, or more generally the epistemology and the philosophy of science. Physics has long been considered the King of the sciences; the biological, social and cognitive sciences having been relegated to roles of Jacks or knaves, all suffering, to some extent, from 'physics envy'. Physics, in this interpretation, thus stands in for our external world, for ultimate reality and for truth itself, revealed to us only through the veil of our limited cognitions, conceptions and perceptions. The world is simply not what it appears to us to be. There is something hiding away from plain sight, beyond the surface of everyday experience. We have adapted to comprehend the behaviours of things of roughly our own scales of space, that move and change according to our own scales of time. We have difficulty comprehending things that are too small or much too large, things that are too quick or much too slow. All things are thus 'encryptions' of reality in need of decipherment, especially those which lay outside our range of easy understanding. Evolution presents us with reality on a need-to-know basis.

> Leibniz long ago described the procedure of science as like the solving of a cryptogram; and this is a deep and an exact remark. In a scientific research, we have to do the opposite to transmitting information, so that we have to turn the theory of information backward. Instead of sending messages in a known code, we receive messages in an unknown code. The aim of science is to break the code of nature. (Bronowski, p. 429)
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> Like a cryptographer who has captured an enemy agent, [the scientist] can send searching signals which are designed to evoke simple and decisive answers. (Bronowski, p. 432)

We must surveille nature with suspicion. Its truths are steganographically hidden and cryptographically scrambled secrets among the signals that bombard us in daily life. We must first become aware of their existence before they can be found identified and ultimately revealed.

> A hypothesis ... is like the key to a cryptograph, and the simpler it is, and the greater the number of events that can be explained by it, the more probable it is. But just as it is possible to write a letter intentionally so that it can be understood by means of several different keys, of which only one is the true one, so the same effect can have several causes. Hence no firm demonstration can be made from the success of hypotheses. (Leibniz, quoted in Rescher, p. 121)

But just as each effect can have several different causes, and each letter can several different understandings, so too should we suspect that Turing's statement (as well as his entire report) have several different meanings each keyed and targeted to different audiences.

2. At the National Physical Laboratory

Five years after Alan Turing's death in 1954, his mother, Sara Turing, wrote a tribute to her son. Recounting the context of Alan's work at the National Physics Laboratory, an arc rising with optimism and falling with disappointment, she recalled Sir Charles Darwin (grandson of the evolutionist), Director of the NPL, broadcast on the BBC, in November 1946:

> A young Cambridge mathematician, by name Turing, wrote a paper ... in which he worked out by strict logical principles how far a machine could be imagined which would imitate processes of thought ... Broadly we reckon that it will be possible to do arithmetic a hundred times as fast as a human computer, and this, of course means that it will be practicable to do all sorts of calculations outside the scope of human beings. (S. Turing, p. 79)

It might be worth noting Darwin's emphasis on doing 'arithmetic a hundred times as fast as a human computer'. Notwithstanding the fact that a transcript of the entire broadcast was not available to me, the project seemed focused on advancing the work of computers, *who* do calculations, not computers, *that* do calculations. Computers in those days were those persons doing such tasks as figuring actuarial, accountancy, statistical and engineering tables. The focus was not on emulating creativity or intelligence. Sara introduced the difficulties that led to Turing's resignation:

> In August 1947 my husband died. Alan, disappointed with what appeared to him the slow progress made with the construction of ACE, and convinced that he was wasting time since he was not permitted to go on the engineering side, asked for a sabbatical year. (S. Turing p. 86–87)

> While away in Cambridge he wrote a report on "learning machines" for the National Physical Laboratory whither he returned about May 1948. As progress on the ACE had not come up to his expectations he sent in his resignation from the Scientific Civil Service. (S. Turing, p. 89)

Soliciting a comment from the NPL, she received this ambivalent summary of Alan's contribution to the development of the ACE. E.T. Goodwin, Superintendent of the Mathematical Division of the NPL, wrote to Sara Turing in 1957, three years after Alan's death in 1954:

> In the early years after the war Alan produced what we call the 'logical design' of a large computer which was to be called 'The ACE' or Automatic Computing Engine. The Laboratory was very doubtful of its ability to produce successfully what was then so ambitious a machine and, at about the same time when Alan took his sabbatical year at Cambridge, it was decided to produce a small version which would be entitled the Pilot Ace. Though the basic ideas behind this machine were largely Alan's, you will understand that the detailed arrangement was decided by others. (S. Turing, p. 84)

Nine years earlier, Sir Charles Darwin, National Physics Lab Director, noted in the minutes of the Executive Committee, was much less diplomatic:

> [Turing's report is a] schoolboy's essay ... not suitable for publication. (Darwin quoted in Copeland, p. 401)

Turing quit the NPL after his sabbatical, breaking an agreement that he would return to work for another two years. His 'Intelligent Machinery,' subtitled 'A Report', was clearly not viewed as such by Darwin. It was a report on Turing's vision of work he had wanted to complete, but could not complete at the NPL.

> Everyone had been slow to adjust to the realities of the post-war period. In expecting the Post Office to cooperate on the [mercury] delay lines, Alan had been as unrealistic as any of the administrators ... Perhaps Darwin never really wanted a computer, just as the Admiralty had not really wanted to know where German ships were. The 'support' of Travis and the Ministry of Supply had not in fact made any difference to the bureaucratic inertia. Darwin and Womersley had played at being commissars while Alan remained the humbler worker and peasant ... [Turing] was not given a chance to make a mess of it for himself, as was his right as the creative worker ... for in the end every successful computer project had to solve the problem of integrating 'mathematical' and 'engineering' skills, which was exactly what he [Turing] longed to do. (Hodges, p. 376)

It was also manifesto and critique. At the beginning of 'Intelligent Machinery', Turing outlines 'some of the reasons' why 'it is assumed without argument' that it is not 'possible for machinery to show intelligent behaviour'. This likely was an opening salvo aimed directly at Sir Charles Darwin (Director of the NPL) and J.R. Womersley (Superintendent of the Mathematics Division), a confrontation with his superiors who were skeptical of his agenda. Turing resented the compartmentalisation of intellectual activity, in academia and at the NPL.

> Despite his resignation, and all the embarrassment that surrounded it, he completed a report for the NPL in July and August 1948. Its almost conversational style reflected the discussions he had pursued, many at Bletchley, in advancing the ides of *Intelligent Machinery*. Although nominally the work of his sabbatical year, and written for a hard-line technical establishment, it was really a description of a dream of Bletchley Park, and reviewed in an almost nostalgic way the course of his own life rather than contributing to any practical proposals that the NPL might adopt. (Hodges, p. 377)

During his sabbatical at Cambridge, he saw an example of how research should be done, which furthered his frustrations with the NPL.

> [Alan's] mind still straddled mathematics, engineering and philosophy in a way that the academic structure could not accommodate. Temporarily the war had resolved his frustration, giving him something to do that was intellectually satisfying, yet which actually worked. But that was over now, and instead of being drawn in, he was being pushed out... At Cambridge, the computer was firmly in the grasp of M.V. Wilkes ... (Hodges, p. 374)

Turing's correspondence between cryptography (mathematical designs) and physics (engineering physical instantiations of those designs) can be seen as a manifesto to bring down the walls of separation the administrators had erected at NPL. One can almost hear the call to unite theory with practice, mental work with physical labour: 'mathematicians and engineers unite'! He wanted freedom to move freely between the conceptual world of mathematics with the physical world of engineers. Turing was quick to appreciate and appropriate the structure of Wilkes project:

> One point concerning the form of organization struck me very strongly. The engineering development work was in every case being done in the same building with the more mathematical work. I am convinced that this is the right approach. It is not possible for the two parts of the organization to keep in sufficiently close touch otherwise. They are too deeply interdependent. We are frequently finding that we are held up due to ignorance of some point which could be cleared up by a conversation with the engineers, and the Post Office find similar difficulty; a telephone conversation is seldom effective because we cannot use diagrams. Probably more important are the points which are misunderstood, but which would be cleared up if closer contact were maintained, because they would come to light in casual discussion. It is clear that we must have an engineering section at the ACE site eventually, the sooner the better, I would say. (Turing cited in Copeland p. 397)
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> [Wilkes] was in full control, without a Womorsley or a Darwin to get in the way, and working much as Alan would have liked to. The barricade between mathematics and engineering never arose. It was enough to show the folly of NPL policy .... (Hodges, p. 375)

The situation at the NPL was markedly different, design and engineering were separate:

> Little progress had been made on the physical construction of the ACE. The actual engineering work was being carried out not at the National Physical Laboratory but at the Post Office Research Station, under the supervision of Turning's wartime Associate Flowers. (Copeland 395)

According to Sara Turing, Alan coped with the stresses of the logistics of this separation in an uncustomary way.

> When, after the war, the Post Office was engaged in research on computers Alan was sometimes required to attend conferences at Dollis Hill and visit the Post Office laboratories. He disliked complicated cross-country journeys ... so he usually ran the fourteen miles from Teddington [the location of the NPL] to Dollis Hill. (S. Turing p. 86)

Alan's passion to bridge the gap between theory and practice was acquired at an early age:

> Unlike most mathematicians, Turing liked to get his hands dirty building things. To implement an automatic code machine he began building a binary multiplier using electromagnetic relays, which were the primary building blocks of computers before vacuum tubes were demonstrated to be sufficiently reliable. Turing even built his own relays in a machine shop and wound the electromagnets himself. (Petzold, p. 127)

The NPL was late to recognise its own lack of progress, and Womersley reported in the Executive Committee of the NPL on 20 April 1948:

> The present position of this project gives no cause for complacency and we were probably as far advanced 18 months ago ... There are several competitors to the ACE machine, and of these, that under construction at Cambridge University under Professor (sic) Wilkes, will probably be the first in operation. (Hodges, p. 375)

The cause was also recognised too late, at least for Turing:

> "At the end of April an NPL minute spoke of the need for en electronics group working 'together in one place as a whole in close contact with the planning staff at the Mathematics Division.'" (Copeland 397–98)

Cryptography's correspondence to physics, discursive code for his desire to see the engineering efforts of the Post Office electronics group re-established at NPL in house, was meant to press for closer collaboration between the hardware developers, the engineers, and the software developers, the designers in the mathematics department. He further conceded that developing the machine itself (the engineering) would be much more difficult than producing the design and instructions for it (the mathematics). Under this interpretation, Turing invoked the camaraderie that existed at Bletchley Park during the development of the Bombe to decrypt Enigma messages.

It is interesting that Turing includes the Brunsviga pinwheel calculator at the bottom of his list of capacities of various machines with a memory of 90. It may have served both as a reference to a machine that everybody knew and simultaneously as a dig at the bureaucratic establishment that frustrated his attempts to bring the ACE to life. The Brunsviga had long been advertised as having 'brains of steel', and an icon riveted to each machine showed an image of a head in cutaway revealing clockwork gears for brains. For most human computers of the time, the Brunsviga was the workhorse they employed. Did the Brunsviga in that list stand in for Darwin's limited vision of Turing's project as rote arithmetic (as expressed in his BBC broadcast of 1946)? Did it evoke a limited and unimaginative future for intelligent machines, the equation being: (Brunsviga / thinking machine) = (creative workplace / NPL)? Double and even triple Brunsvigas were not unheard of but Turing chose the single as his example.

3. A computational world

If cryptography, i.e., cryptanalysis, is the search for the design of the Enigma machine and the protocols of its use, the hardware and software of an electromechanical computer, then it is also the search for the design of the natural world and the protocols that govern it, the hardware and the software of the computer on which the world as we experience it is run.

The correspondence that Turing draws between cryptography and physics is much richer than it first appears, much richer than that drawn by Newton or Leibniz. Based upon his secret work in developing the Bombe at Bletchley Park, an electromechanical computer with a dedicated program, invoking cryptography as 'as perhaps the most rewarding application' of the ACE, as well as the correspondence between 'cryptography' and 'physics' in his report would have brought that entire experience into the argument he was making. It's uncertain whether Darwin, Womersley or others knew about Turing's work breaking the Enigma. Flowers, who was with him at Bletchley Park and was now associated with the NPL, may have made the connection.

What Turing had done at Bletchley was to construct one enhanced electromechanical computer, the Bombe, to predict the operation of another electromechanical computer, the Enigma. The Bombe was a multiplicity of Enigmas and the project for the Bombe was to retrodict and discover the system (construction), settings (initial configuration), and data (cleartext) fed into the Enigma which would produce the data (ciphertext) that the listening stations had intercepted. He was recursively using one computer to mimic the behaviour of another, of machines represented inside other machines, of mathematics contained inside other mathematics, or in modern parlance computations nested inside computations. In his correspondences and parallels he is applying this same recursivity to physics, suggesting in the discursive style of his time that 'it's mathematics all the way down', or as we might say now, 'it's computation all the way down'. From top to bottom, from thought to whatever underlies physics, all science can be seen as mathematics writ large, that is, computation.

> Dr. Warren McCulloch, professor of psychiatry at the University of Illinois College of Medicine goes further: he says that the brain is actually a computer, and very like computers built by men. (Anon, p. 56)

Alan may have felt some sense of vindication when that statement appeared, as it seems that was the subtext of much of what he had to say in his report. The cover of *TIME* magazine on January 23, 1950, was adorned with Boris Artzybasheff's illustration of a computer examining its own progress and deciding what next to do and the caption, 'Mark III, Can Man Build a Superman?' 'At work, it roars louder than an Admiral', (Anon, p. 55). In two short years the 'computing machine' was taking on the appellation of 'computer' and the human 'computers' of the days before were now becoming 'human calculators' or simply 'human beings'. 'Computation' was gaining popularity. Those who designed these devices no longer were solely among the ranks of mathematicians, but were in the process of becoming 'computermen'.

What is computer science and computation? Frequently they stand in for all the algorithmic processes that we see in nature. Increasingly, the machines we build, computers, are seen merely as technological instantiations of computational phenomena that we discover observe in nature.

> Computer science is no more about computers than astronomy is about telescopes. – E.W. Dijkstra (Flake p. 23)
>
> Computer science is not about computers. It's the first time ... that we've begun to have ways to describe the kinds of machinery that we are. (Minsky 1996)

We have an emerging computational philosophy and epistemology of science. The subject is taken up explicitly as in *Computational Philosophy of Science* (Thagard). The possibility is quietly implied by the emergence of readily apparent patterns from computational rules in nature, such as *The Computational Beauty of Nature* (Flake), and Prusinkiewicz's series, *The Algorithmic Beauty of: Plants* (Prusinkiewicz), *Seaweeds, Sponges and Corals* (Kaandorp), and *Seashells* (Meinhardt). It does not offend our sense of self importance to accept computation as motivating 'lesser' forms of life, but it is still a controversial subject for the human and social sciences. Nevertheless, the RechnenderGeist has spread raising new multiagent explanations in the form of Artificial Societies from dying single-cause models in economics:

> What "sort of science" are we doing? ... [Our] aim is to provide initial microspecifications (initial agents, environments, and rules) that are *sufficient to generate* the macrostructures of interest. We consider a given macrostructure to be "explained" by a given microspecification when the latter's generative sufficiency has been established. (Axtell & Epstein, p. 177)

Horowitz carries this idea forward, from quark to quasar, in his compelling and ambitious book *The Emergence of Everything*. My own field of Anthropology has been slow to follow suit, preferring to privilege the influence the role of the individual and of top-down rational causation over that of the population and of bottom-up emergence inhuman culture. Artificial culture has yet to gain momentum (Gessler).

Among complex systems, we encounter the emergence of the entailments of processes operating at one local scale (of space, agency or time) to forms taking shape at another global scale. We witness global patterns of behaviour emerging from populations of local rules. It is only in the interaction of those local rules that the global pattern come into being. Nowhere among those individual rules would we find any indication of what they will produce. Without those local rules in constant play, the global world would not appear.

Reluctant to be seated among the advocates of 'the world is computational from bottom up', Stephen Wolfram enlists 'correspondences' as did Alan Turing in defining his 'Principle of Computational Equivalence':

> Whenever one sees behavior that is not obviously simple [i.e. complex] — in essentially any system — it can be thought of as corresponding to a computation of equivalent sophistication. (Wolfram, p. 5)
>
> The great historical successes of theoretical science have typically revolved around finding mathematical formulas that ... directly allow one to predict the outcome [of a particular system] ... The Principle of Computational Equivalence now implies that this will normally be possible only for rather special systems with simple behavior... Other [more complex] systems will tend to perform computations that are just as sophisticated as those we can do, even with all our mathematics and computers. And this means that such systems are computationally irreducible — so that in effect the only way to find their behavior is to trace each of their steps, spending about as much computational effort as the systems themselves. (Wolfram, p. 6)

Konrad Zuse, who designed and built the world's first working electromechanical, programmable, fully automatic computer, the Z-3, in 1941 tackled the problem of a computational universe head-on by taking the offensive. In 1969 he introduced the term 'automaton theoretical way of thinking' in his paper 'Rechnender Raum' or 'calculating space' (Zuse, p. 7). In it he takes up the proposition that the cosmos might operate as a cellular automaton. He examines the foundational principles of physics one by one, evaluating the possibility of subsuming each of them under the entailments of an appropriate cellular automaton. Nowhere does he find conclusive evidence to dismiss his proposition out of hand. His overall project is clear, but a quotable few lines summarizing his intent disappear among the details of his arguments.

> The question therefore appears justified whether data processing can have no more than an effectuating part in the interplay [between mathematics and physics] or whether it can also be the source of fruitful ideas which themselves influence the physical theories. (Zuse, p. 1)
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> Such a process of influence can issue from two directions ... 2. A direct process of influencing, particularly by the thought patterns of automaton theory, the physical theories themselves could be postulated. This subject is without a doubt the more difficult, but also the more interesting. (Zuse, p. 2)
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> The first result of viewing the cosmos as a cellular automaton is that the single cells represent a finite automaton. The question to what extent it is possible to consider the entire universe as a finite automaton depends on the assumption which we make in relation to its dimensions. (Zuse, p. 70)
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> In view of the possibilities listed, it is clear that there are several different points of view possible: ... (3) The possibilities arising from the ideas of calculating space are in themselves so interesting that it is worthwhile to reconsider those concepts of traditional physics which are called into question and to examine their validity from new points of view. (Zuse, p. 93)

In like fashion, Ed Fredkin posits the existence of 'the Ultimate Computer' residing in a universe he calls 'Other'. His argument is also detailed but can be summarised more clearly:

> The answer lies in the amazing consequence of the simple assumption of Finite Nature. As we have explained, Finite Nature means that what underlies physics is essentially a computer. Not the kind of computer that students use to do their homework on, but a close cousin; a cellular automaton. Not knowing the details of that computer doesn't matter because a great and tragic British mathematician, Alan Turing proved that we don't need to know the details!
> What Turing did in the 1930s was to invent the Turing Machine. It was a way to formalize all the things that a mathematician could do with pencil and paper. The result proves that any ordinary computer, given the proper program and enough memory, can do what any other computer can do. It can also do what any mathematician can do; if we only knew how to write the program! Finite Nature implies that the process underlying physics is a kind of computer; therefore it is subject to Turing's proof. This means that there is not just one kind of underlying computer, but there are many possible equivalent computers. Of course some are simpler, some are more elegant, some use the least amount of various resources, some are faster... Once we have figured out that it's a computer at the bottom, we already know a lot even if we don't know what kind of computer would be most efficient at the task.
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> As to where the Ultimate Computer is, we can give an equally precise answer, it is not in the Universe - it is in an *other* place. If space and time and matter and energy are all a consequence of the informational process running on the Ultimate Computer then everything in our universe is represented by that informational process. The place where the computer is, the engine that runs that process, we choose to call *"Other"*.

Jürgen Schmidhuber explores a philosophy and epistemology of computation with a lighter touch:

> A long time ago, the Great programmer wrote a program that runs all possible universes on His Big Computer. "Possible" means "computable": (1) Each universe evolves on a discrete time scale. (2) Any universe's state at a given time is describable by a finite number of bits. One of the many universes is ours, despite some who evolved in it and claim it is incomputable. (Schmidhuber, P. 201)
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> **Conclusion**. By stepping back and adopting the Great Programmer's point of view, classic problems of philosophy go away. (Schmidhuber, P. 208)

Marvin Minsky expands upon Schmidhuber's 'conclusion' above:

> Fifty years ago, in the 1940s and 50s, human thinkers learned for the first time how to describe complicated machines. We invented something called computer language, programming language, and for the first time people had a way to describe complicated processes or complicated machines, complicated systems made of thousands of little parts all connected together ... Before 1950 there was no language to discuss this, no way for two people to exchange ideas about complicated machines. But why is it important to understand? Because that's what you are ....
> Computer Science is a new philosophy about complicated processes ... about Artificial Life, about natural life, about Artificial Intelligence [and] about natural intelligence ... So all [prior] philosophy, I think, is stupid. It was very good to try to make philosophy. Those people tried to make theories of thinking, theories of knowledge, theories of ethics, and theories of art, but ... they had no words to describe the processes or the data ... So I advise all students to read some philosophy, and with great sympathy. Not to understand what the philosopher said, but to feel compassionate and say, "Think of those poor people years ago who tried so hard to cook without ingredients, who tried to build a house without wood and nails, who tried to build a car without steel, or rubber or gasoline." So look at philosophy

> with sympathy. But don't look for knowledge. There is none. Remember whenever you see ancient wisdom that still seems smart, what does it mean? It means that the ancient wisdom has something wrong with it that keeps people from replacing it for a long time. (Minsky 1996)

No less intellectually stimulating, and on a lighter note, the possibilities are often further explored as fiction. Among the most interesting are short stories such as Stanislaw Lem's 'Non Serviam' (Lem), novels such as Greg Egan's *Permutation City* (Egan) and films such as Josef Rusnak and Daniel F. Galouye's, *The Thirteenth Floor* (Rusnak).

Is our Universe, at its base, computational? What does it mean to make or refute this claim? Are debates, both pro and con, simply language games? Perhaps they are, but the games being played are oftentimes complex and have serious consequences. Such games are symptoms that expose the inability of spoken language to represent and describe, and our inability to understand and explain certain complexities in our world. Computer languages, on the other hand, may provide correspondences that are richer, that capture many facets of reality more completely than can natural languages. Moreover, by pressing 'run', they spin out the entailments of statements they contain in greater detail and more consistently than discursive arguments following an assertion. The claim that we are patterns that emerge from processes operating at a smaller scale, provides us with more inspiration, insight and wonder into the wonders of this world, than does its negation.

Sara Turing, Alan's mother, wrote:

> Some years later Alan remarked that the daily papers were many years ahead of him, opening even his eyes in wonder, so far did they outstrip him in their forecasts. (S. Turing, p. 80)

Alan would have liked to have joined us in this discussion, and perhaps he has, as there is a little of Alan Turing in each of us.

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Stephen Wolfram looks to reconcile —

INTELLIGENCE AND THE COMPUTATIONAL UNIVERSE

What will it take to create artificial intelligence? The only clear example of intelligence that we have traditionally had is human intelligence. But what aspects of human intelligence are somehow essential to the notion of 'intelligence', and what are merely side effects of our particular biological implementation?

In Turing's day it was known that the brain operated in a largely electrical way – and it was clear that all sorts of devices could be constructed with electronics. But what was the secret that let a brain show intelligent behaviour? Was it some particular architecture that could be emulated with electronics? Or was it something about the way information was provided? Or something else?

I don't think Turing ever imagined that his Turing machines would be equivalent to brains; he was sure there was something fundamentally more to brains. But of course his intuition did not have the benefit of all our experience with actual computers, with what they do, and with the experiments we can do with them.

In my own case, my view of artificial intelligence has changed completely over the past 30 years. And one of the important consequences of the change is that I came to believe that the Wolfram|Alpha 'Computational Knowledge Engine' (Wolfram) should be possible – and then proceeded to build it.

What precipitated the change in my views was the experimentation I did on the computational universe in connection with *A New Kind of Science* (Wolfram, 2002). Normally when we think of computers we imagine constructing machines or programs for specific purposes – to perform tasks we want.

And certainly that is what Turing had in mind when he set up Turing machines, or discussed how 'intelligent machines' could be built.

Originally motivated by natural science, however, what I did was to explore the general universe of possible programs – starting with simple programs that one might set up at random, or by enumeration. And what I found – first in the context of cellular automata – was that even extremely simple underlying rules are capable of producing behaviour of in effect arbitrary complexity.