

Alan Turing, Turing Machines and Stronger

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This positional paper claims that the achievements of Alan Mathison Turing in computer science and informatics are comparable to those of Albert Einstein in physics. Turing's contributions are presented through his most important events and achievements, particularly through the concept of the hypercomputer; that is, computers that are stronger than the Universal Turing Machines. The paper analyzes several essential AI and human-intelligence concepts that Turing introduced. Part of the paper discusses Donald Michie, Alan Turing's co-worker and contemporary and an honorary member of the Jozef Stefan Institute. Even though 2012 marks a century since Turing's birth, he remains largely unknown around the world. This paper makes an appeal for Turing's full recognition and acknowledges contributions to Turing's career.

Povzetek: Prispevki Alana Turinga so predstavljeni s tezo, da je za računalništvo njegov prispevek tako pomemben kot prispevek Alberta Einsteina za fiziko.

1 Introduction

Alan Mathison Turing (23rd June 1912–7th June 1954) was a British mathematician and computer scientist. He invented a formalization of the concepts of “algorithm” and “computation” with the Turing machine, which can be considered a model of a general purpose computer. He also decoded the German Enigma machine (a corresponding book cover is presented in Figure 1).

In 2012, the centenary of Turing's birth, a number of Turing-related events were held around the world. Lectures and publications about Turing were made in Slovenia in the first half of 2012, such as [9, 10], but the most essential event was a conference in October, dedicated to Alan Turing and 20 years of Slovenian Artificial Intelligence Society, entitled “100 Years of Alan Turing and 20 years of SLAIS” (<http://is.ijs.si/is/is2012>). Among the world-renowned researchers who presented at the conference were Stephen Muggleton, Natasa Milic-Frayling, Albert Bifet, Claude Sammut, and Joao Gama. At the opening ceremony, Professor Dr. Ivan Bratko received an award for life-long achievements in artificial intelligence, both in Slovenia and internationally.

The following are some of the key dates related to Turing from our perspective:

- 1912 – Turing's birth
- 1936 – Creation of the Turing machine
- 1932–42 – Enigma decoded
- 1950 – Creation of AI, Turing test

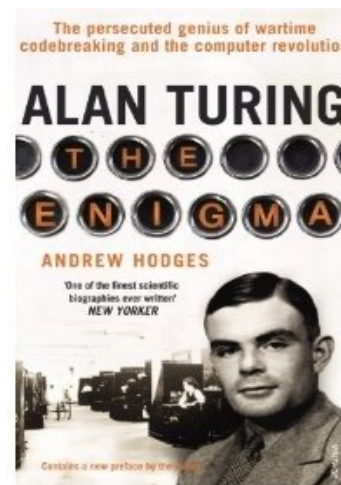


Figure 1: A book about Alan Turing, published in 2012.

- 1954 – Turing's death
- 2007 – Death of Donald Michie
- 2009 – Turing's official rehabilitation
- 2012 – Centenary of Turing's birth

This paper analyzes some of these events. Section 2 discusses Turing's predictions of how to obtain machine intelligence, while Section 3 examines Turing's machine concepts. Section 4 deals with hypercomputing, and Section 5 with the Turing test. Donald Michie and Alan Turing are represented through the Slovenian connection in Section 6, before Section 7 concludes.

2 Turing’s predictions about MI

In 2013, AI Communications will publish Stephen Muggleton’s article entitled “Alan Turing and the development of Artificial Intelligence” [16]. The article analyzes Turing’s predictions for the development of artificial intelligence through his 1950 “Mind” paper [22]. The novelty of Muggleton’s article is that it examines the article published in 1950 from contemporary perspectives. Several of the issues that Turing raised in the Mind paper are as relevant and interesting as at any time. For example, Turing himself proposed three alternative possible ways to achieve artificial intelligence: by programming; by ab initio learning; and by combining several approaches such as learning, logics, probabilistic computing, and using knowledge. Turing also proposed the Child Machine, a machine that enabled learning as an infant. (Coincidentally, in 2012 neuroscientists managed to implant devices into the human brain, enabling tetraplegic patients to control binded artificial limbs, and later learned to improve performance in a way similar to how children do. See, for example, http://journals.lww.com/neurosurgery/Fulltext/2013/02000/Robotic_Arm_Control_Using_Extracellular_Action.3.aspx).

Over the last 50 years, AI researchers have tried all three of the above-mentioned approaches. Some systems like CYC (https://twitter.com/cyc_ai), which have been running for decades and are still very much alive, are based on humans imputing large amounts of knowledge, which an average human possesses, into a computer and adding several simple computing mechanisms. The other approach can be characterized as machine learning or data mining, which is currently one of the most successful areas of artificial intelligence. However, these systems clearly lack human properties and it seems that Turing was correct in denoting this approach as incapable of achieving true human-level artificial intelligence. Even programs like Nell (<http://www.cs.cmu.edu/~tom/>), one of the top AI self-learning programs from the Web, seems to have been saturated after successful learning of words and their relations.

The third approach is clearly the most promising for further research, both when Turing proposed it and today. As Steven Muggleton wrote in the closing remarks of his paper, AI and even Web systems like Google have significantly influenced the way we live today. Despite the major technological achievements that have occurred recently, several of Turing’s ideas and discussions are as valid today as they were over 60 years ago – many lifetimes ago in information-society terms.

3 Turing machine, TM

Although Turing studied several areas related to mathematics, computer science, and artificial intelligence, his main discoveries are probably related to the Turing machine.

In 1936, Turing published a paper about the Turing machine (TM), the Universal Turing Machine (UTM), and the halting problem. He was interested in the undecidability of formal systems, as was his professor, David Hilbert. An undecidable problem is a decision problem for which it is impossible to construct a single algorithm that always leads to a correct yes/no answer. A decision problem is any arbitrary yes/no question on an infinite set of inputs.

Formally [19], a decision problem A is considered to be decidable or effectively solvable if A is a recursive set. A problem is considered to be partially decidable, semidecidable, solvable, or provable if A is a recursively enumerable set. Partially decidable problems and any other problems that are not decidable are referred to as undecidable. In computability theory, the halting problem is to decide whether the program finishes running or will run forever, given a description of a program and a finite input.

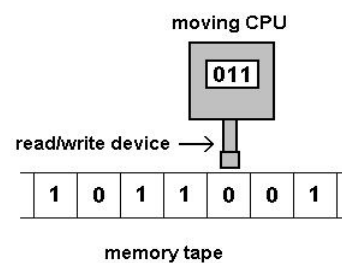


Figure 2: The Turing machine – a formal computing mechanism.

By constructing a counterexample, Alan Turing proved that a general algorithm running on a Turing machine that solves the halting problem for all possible program-input pairs cannot exist. He connected two Turing machines to each other in such a way that one stops when the other does not, creating a logically impossible situation. Therefore, since there are algorithms (programs) that no other algorithm can decide whether it will stop or not, the halting problem is undecidable for Turing machines. Another simple explanation related to algorithms is a version of the halting problem. The program:

```
while True: continue;
will loop forever, but the program
while False: continue;
```

stops very quickly. If we have a function “stops(x)” that takes a program X and returns true if X stops, we can make a program:

```
program p(x): while stops(x): Continue;
This program P takes program X and runs forever if X
does not run forever.
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What happens if we run program P on itself; i.e., $X=P$? This is the essential self-reference that causes the logical impossibility: P must work on every possible program, so it must be able to work on program P, so we can say P runs forever if P does not run forever. That is, by definition, not possible; hence, such a program does not exist for all possible situations.

Turing was not the first person to provide new discoveries regarding undecidability, since it was one of the most important open questions at that time. Church and Gödel presented their theorems first, but to a lesser extent than Turing. Gödel published his incompleteness theorems [18] as early as 1931. A weaker form of his first incompleteness theorem is a consequence of the undecidability of the halting problem. This weaker form differs from the standard statement of the incompleteness theorem, which means that the axiomatic system is a necessity if one wants to prove all true statements about natural numbers. There are actually two issues: provability and truth. In the first case the issue is just about proving, while in the former it is about being true but not provable. In both cases, a formal system contains statements that are true and cannot be proven, even though there are sentences (algorithms, programs, theories) that cannot be proven regardless of their truth value [1]. Turing's contribution was in proving the concept regarding computability (with regard to computing) and presenting it in algorithmic form, while Church and Gödel presented their conclusions as mathematical theorems. It was only discovered later that the concept is basically the same.

The importance of the Turing machine is that it does not consist of mathematical equations and symbols; rather, it is a formal computing mechanism, as presented in Figure 2. It consists of a simple head; that is, a simple read/write device and a tape with cells. Each cell contains just one symbol. When the head is above one cell, it can read the symbol in the cell or write a symbol into the cell. It does not matter whether the head moves or the tape, but one move is to one cell left or right. The head executes a program; that is, an algorithm that is attached to this head.

This computing mechanism represents the simplest and best known model of computing and of the digital computers we use today. Although there are disputes, some of which are looked at in this paper, the Turing machine is not importantly affected by them. For example, theoreticians are quick to point out that the Turing machine needs a tape of unlimited size in one direction (that is, an unlimited data storage equivalent), which means that computers are not true equivalents of the Turing machine, but rather a finite automata (albeit huge ones). This argument seems somewhat superficial. Surely, if the computer memory is big enough, then the difference is meaningless in all but theoretical terms. Memory capacities in computers do not represent a bottleneck in computing, so there is no need to worry about them.

In summary, the Turing machine represents such a basic computing concept, or computing principle, that it can be compared to Einstein's relativity principle in terms of importance and nature. Indeed, both are neither axioms nor theorems, but principles, one describing digital or symbolic computers and the other time-space relations. Similarly, both concepts remain valid for our current lives even though several decades have passed since they were first formulated. Both concepts are also essential for our understanding of the world – without

Einstein we would not be able to understand our universe, and without Turing we would not be able to understand computers and computing.

4 Stronger than Turing machines - hypercomputing

The term “hypercomputation” was introduced by Copeland and Proudfoot in 1999 [2]. Machines are referred to as hypercomputers or super-Turing computational models if they are, in principle, stronger than the Turing machine, which means that they can solve tasks that the Turing machine cannot. The term super-Turing computing usually denotes physically realizable mechanisms. Hypercomputers and super-Turing computational models include the computation of non-Turing-computable functions, following super-recursive algorithms. Turing himself introduced stronger machines than the universal Turing machine. An example is a Turing machine that includes an oracle capable of correctly answering any question with Yes or No. However, the purpose of this section is simply to analyze machines or beings that do not need a superficial component, but are stronger than Turing machines.

Hypercomputing is related to several issues, including the question of human computing power compared to computing mechanism and computers. Consider, for example, the Church-Turing thesis [24]. It states that any function that is algorithmically computable can be computed by a Turing machine. Hypercomputers compute functions that a Turing machine cannot, which means that they are not computable in the Church-Turing sense. Some publications have indicated that no physical machine can be designed to surpass the Turing machines and that it is not possible to construct a counterproof. In other words, the hypercomputer ideas could be hypothetical and physically non-existent. In principle, however, there is no proof that hypercomputers are impossible in mental computational issues, just because they are not physically realizable. Accepting philosophical viewpoints such as dualism is sufficient for hypercomputers to become theoretically possible, if ever a concrete version were not designed in the form of a computing machine.

Several authors, such as Roger Penrose [17], have opposed the notion that computers are as powerful as digital computers, directly indicating that humans either possess stronger mechanisms than Turing machines or mechanisms that, while not in principle stronger, are so different in practical computer terms that computers cannot compete with them under real-life circumstances due to huge differences in complexity. In other words, the human brain is either stronger in principle or in reality for most real-world tasks.

The halting problem is one problem that a Turing machine cannot solve. Some hypercomputers can simulate a program for an infinite number of steps and tell the user whether or not the program halted. Some authors have claimed that the halting problem can be solved by humans even without using the additional

information that is known to make it possible to solve the halting problem.

Therefore, the halting problem can be solved, even by a Turing machine, if additional information is provided; however, in the same circumstances only hypercomputing mechanisms and humans can solve the problem. Therefore, humans are computationally stronger than computers.

For a hypercomputing model, the author of the present paper introduced the Multiple Turing Machine, as presented in Figure 3. Unlike the multi-tape Turing machine, this model consists of two universal Turing machines, each of which writes on each other program, while at the same time obtaining information from the open outside world. The model is based on the principle of multiple knowledge [5]. The weak version of this principle states that a sensibly integrated model (or computing mechanism) generally outperforms each single model constituting the basic set of models. The strong version of the principle states that real or human-level intelligence can be achieved only when using the multiple algorithms that apply the principle. Current computer mechanism in digital computers cannot provide the multiple computations. This means that current computers are not as strong as humans in principle, although they are much faster at computing single operations and tasks that do not demand multiple computations. It is important to note that multiplicity may or may not include parallelism; rather, it resonates the interaction concept [23]. The principle of multiple knowledge has several representations and confirmations. In terms of the physical world, it demonstrates a strong similarity to the multiple-worlds theory [3] or the multiverse theory [4]. In both theories, there are a huge number of universes like ours in the super-universe. The open question remains where these universes are. Are they physical or just mental? If they are physical, where are they exactly? Besides the evidently non-problematic mental existence, there are also theories related to the physical existence of multiple worlds.

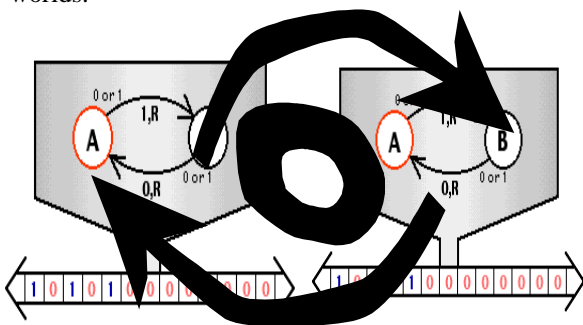


Figure 3: The Multiple Turing machine.

The controversial multiverse theory is based on physical observations that our universe is expanding at an increasingly fast rate, despite there not being enough matter or energy of any kind to support such an increase. However, the existence of multiple coexisting universes would explain the gravity that causes the expansion.

Whatever fascinating these new ideas that enable other kinds of computation, the TM the best corresponds to digital computers while there is no existing hypercomputer in our physical world and no super-universe has yet been confirmed. It should also be noted that for some kinds of computation we now understand the differences compared to the Turing computation. For example, quantum computers do not compute based on 0/1, but on a quantum superposition of the two; that is, in an essentially different computing way. However, while David Deutsch himself originally claimed, around 1988, that quantum computers have a computational power beyond UTMs, they are presently not considered that way, even by Deutsch, who now views them as a way to reduce cryptographic problems from the NP complexity class to the P class (see Shor's result on NP complexity in quantum computing).

The Turing machine and the halting machine are as fundamental concepts and principles as the other principles humans use, such as that of Einstein, and have not changed over time.

5 Turing test

In 1950, Turing published a paper describing the Turing test and a debate about artificial intelligence, which at that time was referred to as "machine intelligence". It was only in 1956 that McCarthy coined the term "artificial intelligence" term and the field started growing.

Regarding the Turing test (Turing 1950), the best known and discussed AI test of all times, the issue is in comparing behaviors of two computing mechanisms (originally one human and one computer) and identifying the computing type of each. There are dozens of different versions of the Turing test, such as a Total Turing Test [12], which includes physical tasks, and a Trully Total Turing test [20], which examines populations of test subjects.

In terms of the latest definitions [8], intelligent systems and intelligence are defined with the ability to learn. As a consequence, all machine learning systems are intelligent and every living being is intelligent including bacteria and plants. However, the Turing test deals with human-level intelligence, which includes testing at that level.

In practical terms, although computers have improved their performance by a factor of 100,000 over the last 20 years, human interrogators separate computers from humans in as many questions as before two decades. The reason is that current computers lack any human-level understanding. By verifying the understanding of any sentence – that is, its semantics – all computer programs display tabula-rasa performance. This is the empirical argument of weak AI, which claims that computers need major improvements in order to approach human-level intelligence and computing [5, 6].

The relation between computers and humans is presented in Figure 4. Computers progress exponentially according to Moore's law. In Figure 4, the x axis is linear and the y axis is logarithmic; therefore, the progress of

computers is presented by a line. On the other hand, humans, in terms of their hardware, remain the same as they were hundreds of years ago. Due to the huge difference in the speed of progress, computers have bypassed humans in an increasing number of areas. For example, computers can beat humans in practically all formal mental games, with only a few exceptions. In 1997, Garry Kasparov lost to the Big Blue IBM computer, while in 2011 another IBM program, named Watson, beat two human world champions in “Jeopardy,” an association knowledge game.

Today, however, humans use computers as tools, analogous to forks, chairs, or cars, not as beings, due to their lack of personality or self-awareness. Computers are purely calculating and information/retrieval tools that enable several services like web or social interaction. Humans using tools can perform better in tasks such as flying an airplane. Computers help us solve more complex information and calculation tasks; therefore our capability to solve problems dramatically increases due to the progress of computers, as represented in the upper line in Figure 4. Furthermore, this line helps understand the Flynn phenomenon of how each generation achieves higher IQ scores than the last. It is mainly due to the improved computers, which have a positive reverse effect on humans. As far as the author can ascertain, this explanation is the first of this kind of the Flynn phenomenon.

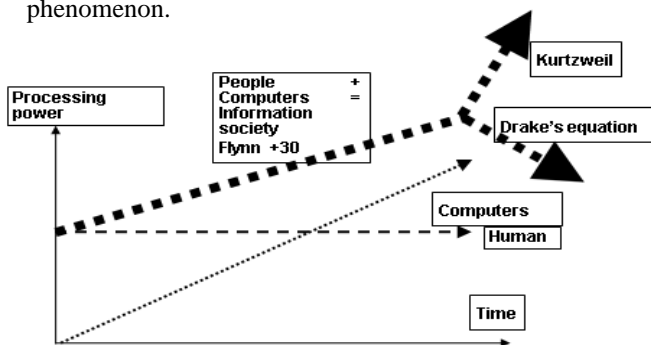


Figure 4: Modern viewpoint on relation between computers and humans.

Where will this progress lead us? According to optimists like Ray Kurtzweil, who was recently employed by Google, the constant progress of human civilization will lead to a qualitative leap forward. According to pessimists, humans are facing dire times, perhaps because of several reasons, such as overpopulation, global heating, and a lack of natural resources. Another grim prospect of human civilization comes from the Drake equation, which says that, based on the number of stars in the universe, there should be several civilizations with which ours should have already made contact. However, these are only possible negative predictions that need not happen.

Like Turing, who predicted true artificial intelligence (albeit by 2000), most scientists agree that true intelligent computers will emerge sooner or later. When that happens, human civilization will indeed leap forward.

6 Alan Turing, Donald Michie, and Slovenia

Slovenia has a strong connection to Alan Turing and his companion Donald Michie. Michie and Turing worked together to decode Enigma, the German encryption machine. By use of electronic machines, the counter-surveillance department where Michie and Turing worked was able to decode messages to German submarines. This has been described as the most relevant civil discovery during the Second World War and that it saved hundreds of thousands of lives. Because it was a secret, not much was known about this issue until decades later when the data became public.

Alan Turing died committing suicide with a poisoned apple, in an analogy to the Cinderella story. His death and sexual behavior (homosexuality was at that time treated as a risk to national security for anyone employed in governmental services and was therefore prosecuted) led to Turing’s legal prosecution. Today, this would be considered a major injustice to a loyal and honorable citizen, and his conviction was only reversed in 2009.

Unlike Turing, Michie [21] went on to have a long and successful career in artificial intelligence. He was also the first person to establish an AI department in any institution in the world. Michie was awarded several established prizes, including the Feigenbaum Medal and the IJCAI award. Michie is especially important for Slovenian AI and the Slovenian society SLAIS due to his cooperation with Ivan Bratko. In recent decades, Michie has often spent one month each year at the Jozef Stefan Institute, in Ivan Bratko’s room. The room is now named the Donald Michie room and is close to the central lecture hall at the institute. Ivan Bratko also spent a lot of time at the Turing Institute in UK, where several Slovenian researchers were invited for short and long periods.

Ivan Bratko, who has been active in many AI areas including machine learning [13], was the head of the AI department at the Jozef Stefan Institute. Due to the successful growth of the field, three departments emerged from the original one. Ivan Bratko is still the scientific head of the Intelligent Systems department. As well as the Donald Michie room, there is also an Alan Turing room, the office of the author of this paper, who in 2010 [7] wrote: “Let this be in memory of Donald Michie as Turing’s contemporary and our dear colleague, and the extreme genius Alan Turing, who marked the lives of every human in the world as hardly anybody else has”. The contributions of Turing and Michie were presented on several other occasions as well [8, 9, 10, 11].

Stephen Muggleton [16], Ivan Bratko, and the author of the present paper established an award named the Michie–Turing Award for life achievements in information society in Slovenia. This is our humble tribute to the great names that will resonate in Slovenia for a long time to come. At this opportunity, we wish to thank the living relatives of Donald Michie and Alan Turing, who agreed to the naming of the award. An

international board will supervise the nominations to guarantee that the award recipients will comply with the desired high criteria. More about the award can be found at http://is.ijs.si/is/is2013/nagrada_is_eng.asp?lang=eng.

The Michie–Turing award was defined during the Alan Turing Conference in 2012 [14] in Slovenia and will be presented for the first time in 2013.

7 Discussion

Entering “Lady Gaga” into the Google search engine produces 400 million hits, compared to 132 million for “Mozart”, 60 million for “Albert Einstein” and just 9 million for “Alan Turing”. Amazon.com contains approximately 10,000 book references for “Albert Einstein”, compared to 1700 for “Alan Turing”. Yet, many scientists, including the author of the present paper, consider the Turing Award to be the computer science equivalent of the Nobel Prize, and Turing himself as the “Einstein of computer science”. Today, several publications refer to Turing as the father of computer science, artificial intelligence, and mathematical biology.

Although it might not be logical to compare the fame of Lady Gaga to that of Turing, why is Turing so unrecognized compared to such geniuses as Einstein or Mozart? What good is it that Turing is widely recognized in computer science and informatics, if the average European has not heard of him but has heard of Einstein or Mozart? The fact that Turing was neglected 60 years ago does not change the fact that he is still neglected now, as criteria such as internet hits indicate.

It should be the responsibility of all scientists, not just the computer science community, but on all scientists to revive the fallen acknowledgement of an extraordinary scientist who was ruined by intolerant bureaucrats. It is only fair that the world accepts Turing as one of one of the most important scientists. Anyone who doubts such a claim should just look around and count the Turing machines embedded in nearby machines or read his seminal works.

We should also remember Donald Michie as Turing’s companion on the list of computer geniuses who changed the world.

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