THE TURING TEST RELIES ON A MISTAKE ABOUT THE BRAIN

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Abstract. There has been a long controversy about how to define and study intelligence in machines and whether machine intelligence is possible. In fact, both the Turing Test and the most important objection to it (called variously the Shannon-McCarthy, Blockhead, and Chinese Room arguments) are based on a mistake that Turing made about the brain in his 1948 paper "Intelligent Machinery," a paper that he never published but whose main assumption got embedded in his famous 1950 paper and the celebrated Imitation Game. In this paper I will show how the mistake is a false dichotomy and how it should be fixed, to provide a solid foundation for a new understanding of the brain and a new approach to artificial intelligence. In the process, I make an analogy between the brain and the ribosome, machines that translate information into action, and through this analogy I demonstrate how it is possible to go beyond the purely information-processing paradigm of computing and to derive meaning from syntax.

For decades, the metaphor of the brain as an information processor has dominated both neuroscience and artificial intelligence research and allowed the fruitful applications of Turing's computation theory and Shannon's information theory in both fields. But this metaphor may be leading us astray, because of its limitations and the deficiencies in our understanding of the brain and AI. In this paper I will present a new metaphor to consider, of the brain as both an information processor and a producer of physical effects. There will also be an analogy between the brain and

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certain tiny biochemical machines called ribosomes, an analogy that may help us finally settle the thorny question of the Turing Test and objections to it, principally the Shannon-McCarthy objection.

The classical computational theory of the mind says that the mind is a computing system similar to a Turing machine, an abstract model of computation with a read-write head that processes symbols on an infinite tape. A universal Turing machine can simulate the input and output of any Turing machine, like a programmable computer. Humans could be taught to mimic a universal Turing machine, but if the human brain were 'just' a Turing machine, then a universal Turing machine would be able to imitate it.

A serious challenge to the computational theory of mind has been the memorizing machine argument originated by Claude Shannon and John McCarthy (respective founders of information theory and AI) two years after Turing's death in 1954, an influential argument with variations including the Blockhead and the so-called Chinese Room arguments, arguments whose crux is that we cannot get from pure syntactical processing to semantic content on the Turing machine or Shannon information theory models, discussed below.

Turing might have replied to these arguments more effectively than the existing replies. Perhaps he would have realized that their basis is in a false dichotomy from his paper 'Intelligent Machinery,' written in 1948 but not published until 1968. After some background, I will describe this mistake and show how it could be fixed with a new model of computation, machines called active information machines. Another example of an active information machine is the ribosome that translates biological information into active material. Then I will discuss potential consequences for neuroscience, cognitive science, and AI that should follow from this new model of biological computation.

1. Origins of the information-processor metaphor for the brain

It was common in the 1940s and 1950s to understand the brain as purely processing information, echoing Shannon's theory of communication, and this understanding was shared by Turing, von Neumann, and many others. The main idea is that the information-input-to-information-output viewpoint of the brain elides the reality of the brain's activity, because in the intervening decades biologists have made many advances, and we now know that individual nerve cells are doing more than just processing information, including producing molecules, movement, and fields. Some neuroscientists and computer scientists recognize this, such as those working in situated and embodied cognition.

This metaphor of the brain as pure-information-processor underpinned Turing's celebrated Imitation Game, also known as the Turing Test, which a computer would pass and thus show intelligence if it replied to questions in a way that is indistinguishable from the way a human would reply (Turing 1950). This test has generated a great deal of interest in philosophy and beyond, and it was opposed by Shannon and McCarthy in the preface of their 1956 volume [34], summarized here.

> "This [Shannon-McCarthy] objection envisages a hypothetical computer that is able to play the imitation game successfully, for any set length of time, in virtue of incorporating a very large–but nevertheless finite–'look-up' table. The table contains all the exchanges that could possibly occur between the computer and the interrogator during the length of time for which the test is run. Clearly an interrogator would have no means by which to distinguish a computer using this table from

> a human respondent. Yet presumably the computer–which does nothing but search the table provided by its (hypothetical) programmers–does not think. In principle, therefore, an unthinking, unintelligent computer can pass the test." (Copeland 2004, The Essential Turing)

This objection was later rephrased as the Blockhead argument by Ned Block, with the observation that there are a finite number of sentences to start a conversation, a finite number of responses that are sensible, of sensible responses to responses, etc. All of these responses could be programmed into a look-up tree and used by a machine to produce "a sensible sequence of verbal outputs" and yet have "the intelligence of a toaster" (Block 1981).

This Shannon-McCarthy objection was also rephrased as the Chinese Room Argument (Searle 1983). Searle-in-the-room knows nothing of Chinese and is in a room with instruction books to produce Chinese character outputs in response to Chinese character inputs. The point he says, is: "if the man in the room does not understand Chinese on the basis of implementing the appropriate program for understanding Chinese then neither does any other digital computer solely on that basis because no computer, qua computer, has anything the man does not have."

Some of most effective counterarguments to these objections have been that one should not view computer programs as pure syntax and no semantics (Boden 1988), and that such a memorizing machine would be impractically slow for any reasonable length of a Turing test (Shieber 2014).

The Imitation Game and its objections all rely on a claim that Turing makes about categories for machines, categories determined by two dichotomies (Turing 1948, in Copeland 2004). The first dichotomy is between discrete and continuous machines. Turing acknowledges that the brain is technically continuous or analog, but observes

that we may as well model or approximate it as discrete or digital. This insight that has been helpful in neural and biological modeling.

Turing's second dichotomy, however, between 'active' and 'controlling' machines is mistaken. Active machines, he writes, produce definite physical effects (beyond small Brownian motion effects such as heat), and as an example he gives a bulldozer. Controlling machines deal purely with information, and as examples he gives the telephone, the ENIAC, and the brain. This dichotomy is false, because the brain both processes information and produces definite physical effects including, we now know: molecules such as neuromodulators and hormones, motion mediated by muscles, electromagnetic fields measurable by medical devices, and physical remodels of itself in processes such as learning and neuroplasticity. We will summarize these physical effects by the word 'action,' which overlaps with, but is not identical to, the concept of behavior in biology and psychology.

Since the brain is a machine that both deals with information and produces physical effects, it would be good to define a new kind of machine that abstracts and generalizes this idea, an *active information machine*, and to develop a theory for these machines that not only combines existing theories, but also allows information processing and dynamical changes to happen simultaneously and in mutually influencing ways.

2. Another Active Information Machine: the Ribosome

There are other active information machines besides the brain: other organs, robots, and the nanoscale machine called the ribosome that translates information into active, information-containing products. Understanding these simultaneous action and information-processing functions of the ribosome should be a useful analogy for how the brain might work as an active information machine, and should allow us to develop a rigorous foundation for a new theory of active computing to underpin a new science of the brain and AI.

The ribosome assembles proteins from the codon sequences forming messenger RNA (mRNA, and codons are nucleotide triplets, such as GAA). A ribosome holds a codon of mRNA and matches it to the corresponding anticodon and thus the corresponding amino acid by a kind of look-up table in the form of transfer RNA (tRNA, each with the anticodon and the matching amino acid). After joining the codon with its anticodon tRNA, it separates the tRNA's matched amino acid (aa, in the case of GAA, glutamic acid) and binds it to the previous amino acid, producing an amino acid string that folds into a protein with the help of the ribosome and proteins called chaperones. Other raw materials include the chemical energy source GTP, and variations of ribosomes occur in all the kingdoms of life.

Software in this analogy includes, roughly speaking, the cell's DNA: various gene-regulatory processes transcribe DNA into RNA and further process it, much like software compiling, into a ribosome-ready strand of mRNA, much like the cell's 'machine code.' More precisely, the software is the mRNA translatome, as it has been said memorably: "Genes don't code; mRNA does" (Wheeler 2007). Using this metaphor of a program for genes has both benefits and drawbacks (Keller 2000, Keller 2002). EXPAND ON THIS?

In the metaphor of the brain as a computer, hardware is usually understood to be the brain, but this can be a bit misleading. In fact the brain is largely made of proteins that are output from mRNA programs, and the ribosome is closer to hardware, though it would be better to call it 'ambiware' because a ribosome is physically made of a combination of software and hardware: RNA and proteins intertwined with each other.

As an active information machine, the ribosome processes the software or information in mRNA and produces an output polypeptide which is physically active and also contains information, though less information than the mRNA.

The collection of biologically occurring proteins is a thin slice in the space of all possible proteins. In theory there are more than 20^{500} possible protein outputs (500 units is the length of a typical protein, but some are 27,000 units long), an enormous number compared to the approximately 10^{80} atoms in the universe. In practice there are actually around two million distinct proteins, selected for by evolution and retained because they perform useful functions such as catalysis.

The existing proteins are biologically meaningful, and this is not 'observer-relative' because differences in protein sequences result in objective differences in biological activity. An example illustrating this is the sickle cell trait, cause by a mutation in the gene coding for hemoglobin, a mutation from GAG to GUG in a particular location. The cell's translation machinery translates the codon GAG to glutamic acid, and the codon GUG to valine. These two amino acids have different chemical properties, rendering the resulting proteins (hemoglobin and hemoglobin S, respectively) chemically and biologically different from each other. Both versions of this protein have persisted, the sickle cell one because it provides some resistance to malaria.

Biological information can thus carry meaning that is intrinsic and independent of an observer.

3. Information Theory and Beyond to Transduction

Applications of information theory in biology are challenging and controversial, sometimes hailed as progress and sometimes criticized as erroneous or distorting (Godfrey-Smith and Sterelny 2016). One question that arises repeatedly is (e.g., Godfrey-Smith 1999): What are the composers or senders of a biological message, and what are its readers or receivers?

Answers have been difficult in part because of cellular feedback mechanisms in which, for instance, proteins made from RNA by ribosomes have effects that regulate gene expression in the nucleus, in turn affecting which new proteins are made. In

this light, ribosome are readers of biological messages, but they are also partially composers of new biological messages through the proteins they make.

Other composers include gene regulatory structures during and after transcription, and other readers include post-translational modifying and signal-recognizing proteins. Broadly speaking, the whole genome, epigenome, enzymes, and gene-regulatory networks work together to create and send an mRNA message, often in response to environmental changes. And the cell or body receives the translated protein messages and their downstream messages such as hormones, using these molecular messages in various cellular processes, including gene expression (see also Griffiths and Stotz 2013).

An objection to the use of information theory in genetics is: "it is perhaps odd to think of this [ribosomal translation] as 'de'-coding, since it was not 'coded' from protein to mRNA in the first place" (Maynard Smith 2000). This objection can be addressed by looking instead at the level of a single amino acid rather than the whole protein, or on the level of a single codon rather than the whole mRNA. At this level of a single codon or amino acid, the ribosomal decoding from codon to amino acid has the counterpart encoding of an amino acid in the tRNA with its matching anti-codon or wobble codon, made by an aa-tRNA-synthetase. The encoding happens (top line of the following table) before the decoding (bottom line). The middle of the table shows what the ribosome holds right before the amino acid (aa) separates from the tRNA to bind to the previous amino acid.

Then the issue of encoding comes down to how these synthetases evolved (see e.g., O'Donoghue and Luthey-Schulten 2003, Sella and Ardell 2006). Life may have originated as a tandem evolution of a variety of interacting short polymers of nucleotides, amino acids, and other molecules like cofactors (Caetano-Anollés and Caetano-Anollés 2015). There also evolved a division of labor between DNA with its stability to store

		anticodon $\xleftarrow{\textit{Encoding synthetase}}$	amino acid
mRNA codon	–	anticodon = tRNA	= aa
mRNA codon		$\xrightarrow{\textit{Decoding ribosome}}$	amino acid

TABLE 1. The genetic code involves both encoding and decoding, with − as the weak bond of a base pair, and = as the bonds within tRNA.

information and proteins with their ability to perform functions, and RNA in between able to store information and to perform a few enzyme-like functions. Ribosomes themselves are at this nexus between information and function, stability and dynamism: information stored in DNA for long-term stability, information stored in RNA for medium-term transmission to ribosomes, and functions performed by proteins that are dynamic.

Information theory has also been applied to neuroscience at the neuron, network, or system level, in a variety of ways (Tishby et al 1999, Dimitrov et al 2003, Cao 2012, Corominas-Murtra et al 2014, Hoel 2017). But there is no consensus yet on the most useful application, and one problem is that abstract information is not enough.

If we were to apply Shannon's information theory to the ribosome we would get the following. The input signal X is mRNA, the channel is the ribosome, and the output Y is the amino acid string. The ribosome channel in this setting is not particularly 'noisy' since it has an accuracy of about 99.99%, with an error about once in 1,000 to 100,000 codons. The rate of ribosomal processing, about 17 codons per second (and since there are 6 bits per codon, that amounts to about 100 bits per second) is less than the ribosome's theoretical Shannon capacity. This expanded version of information theory I will call 'active information theory' (alternative terms could be 'semantic' or 'meaningful information theory'; a compatible point of view is Juarrero 1999).

This setting of ribosome as active information machine is the context for the following table: the ribosome is the transducer T taking input X with a start and a stop codon, and outputting the corresponding amino acid string Y that is the translation of X ('the' translation because of the nearly 100% accuracy).

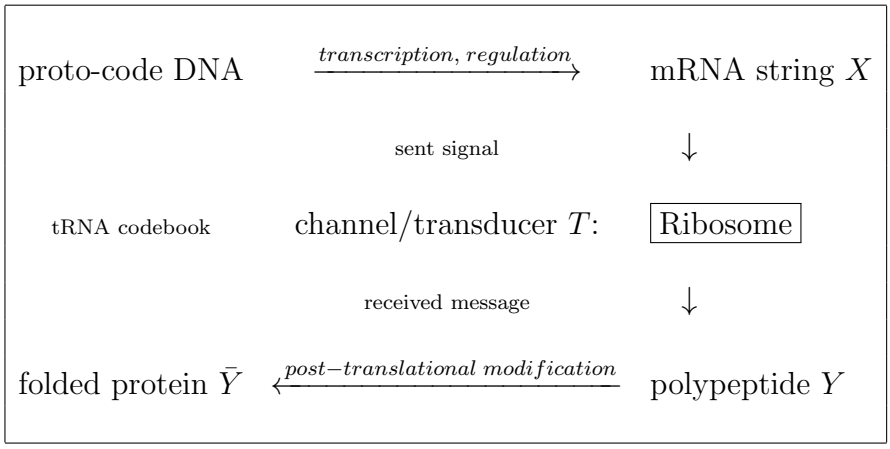

TABLE 2. A diagram of the ribosome as an active information machine translating input information string X into physically active protein $\bar{Y}$.

In order to understand the full ability of a ribosome beyond pure information processing, namely to generate a physically active output polypeptide, we need something more than information theory. A useful concept here is that of a *transducer*, which converts energy or information from one form into another.

This is compatible with the terminology of the mathematical theory of translation (overlapping but not the same as biological translation), developed for compilers of programming languages (Aho et al 1969). We can describe a ribosome as a one-way nondeterministic finite transducer T, as in the diagram above.

A ribosome can be viewed as both an information channel and a transducer. The first emphasizes its information processing ability, changing information from one form (RNA sequence) to another (amino acid sequence); the transducer emphasizes its ability to transform information into a physico-chemical polypeptide that folds into a protein (which may itself be a signal or mechanical transducer). We need both

of these aspects for appreciating the full ability of the ribosome, an *active information machine* that transforms information into physical effects, and syntax into semantics. Appreciating this duality of active information machines could help us to get beyond the metaphor of the brain as purely an abstract information processor, and to grasp it as processing physical information and producing physically active outputs.

4. Countering the Shannon-McCarthy objection and its derivatives

One advantage of viewing brains and ribosomes as active information machines is that we can counter the Chinese Room argument on theoretical grounds, in addition to the practical counterargument of Shieber. First, the premise "Programs are formal (syntactic)" is wrong: It is fair to say that a programming *language* is purely syntactical, but specific programs, while conforming to the formal constraints of the language, are also meaningful (Boden 1988). Indeed most programs have a great deal of content, e.g., the program in which this paper is written. The content and meaningfulness of programs is evident from the existence of semantic analysis (e.g., syntax-directed translation) as an important stage of compiling a program. To be sure, many computer scientists and neuroscientists have ignored this issue and have gone ahead with their programs and experiments, making and discovering useful things. But getting a grasp on how it is possible for semantics to come out of (what looks like) pure syntax should help clarify things.

Mays argued in 1952 that computer programs are all syntax and no semantics; this is flawed, similar to the premise "Syntax by itself is neither constitutive of nor sufficient for semantics." It may be true in some settings that pure syntax is not sufficient for semantics, but this is irrelevant for ribosomes because they transduce information into physical material, and the set of realized syntactically correct strings is a small subset of the space of all potential strings, a subset of inherently meaningful proteins. Most programs and mRNA strings are both syntactically correct and semantically

meaningful, and the high-level source code of DNA results in meaningful structures. Along these lines, it is better to say that the nurtured genome causes both brain and mind, rather than the misleading idea that "Brains cause minds."

Our main example is a ribosome, which is intrinsically computational, not 'observer-relative,' and which produces outputs that have intrinsic physical reality. A ribosome is a machine turning syntax into meaningful chemicals, by reading codon strings and forming meaningful proteins: It reads UAG as a start codon and puts the amino acid methionine in the first place. It then proceeds to read the next codon triplet and place its corresponding amino acid next in the chain, according to the genetic code. When it reads one of the stop codons UAA, UAG, or UGA, it stops and releases the finished chain (except in a case of translational readthrough). For instance, the ribosome translates the codon GAG to glutamic acid, and the codon GUG to valine. These amino acids are meaningfully different from each other, and one way to emphasize the importance of this difference is that if the human gene coding for hemoglobin has a mutation from GAG to GUG in a particular place, then the resulting protein is hemoglobin S, a variant protein resulting in the sickle cell trait.

One objection to the foregoing could be that the genetic code is arbitrary and could have been something else (Stegmann 2004), so it has little meaning. Before the genetic code evolved, the matching of amino acids to codons was probably loose. We see some evidence of this loose matching in the fact that there are variations on the standard code among mitochondria, bacteria, and archaea. But these variations are small, so there must have been a stronger drive towards standardization than the drive towards variation. Indeed the standard genetic code has been shown to be optimal in a technical sense, simultaneously optimizing robustness, diversity, and cost under normal environmental conditions (Tlusty 2008). Robustness means that the genetic code has a bit of error-correcting built in: a number of common mutations

result in the same amino acid or in an amino acid with similar chemical properties, so the resulting proteins may still be functional.

The genetic code could change if environmental conditions were to change enough, for instance, with the high radiation levels of outer space or Mars. Under such different conditions, the standard genetic code might no longer be optimal, especially with respect to robustness under mutations. The fact that the genetic code varies somewhat among the kingdoms of life, however, does not imply that the code is arbitrary.

5. Consciousness: There is no recipe and what it is[1]

A theory of cognition built on active information machines may be a key to finally understanding consciousness. Understanding which interactions in systems of genes, ribosomes, and proteins are the most important may be informed by experiments that find transcriptomic, translatomic, and proteomic correlates of consciousness.

One speculation about consciousness is that it may involve a phase transition to a macroscopic phenomenon like percolation (Cohen et al 2010). Percolation theory models connectivity and communication in graphs, on which neural networks are built: when the connectivity between pairs of neurons is too low, communication on macroscopic scales may be impossible; and when the connectivity passes above a certain threshold, macroscopic communication becomes possible.

Even cooler, some states of consciousness could be like superconductivity. Superconductivity is another phase transition phenomenon, where certain materials at low enough temperatures have essentially zero resistivity, current can flow freely with no loss, and magnetic fields can be expelled, allowing levitation and applications such as MRI machines. (If consciousness turns out to be a macroscopic quantum phenomenon like superconductivity, then brain imaging should strive to take into account the

[1]Apologies to P.R. Halmos

observer effect in physics, that the act of imaging changes the quantum state.) In any case, consciousness could be a 'paraphenomenon': a useful byproduct of the physics of the brain.

A theory of consciousness like superconductors would be testable by studying biological molecules with special conductive properties that also correlate with certain kinds of brain activity–one candidate is neuromelanin (Giacomantonio 2005[2], Bettinger et al 2009, Prescod-Weinstein 2017). This would dovetail nicely with the experimental physics effort to find so-called high-temperature (that is, room-temperature) superconductors. Interestingly, if we could build a superconducting computer, it would be around 500 times more energy efficient than a regular computer, not too different from the brain's energy efficiency. Computing efficiency alone may not suffice for consciousness, but it could contribute.

One reason for the conceivability of a superconductor-like theory of consciousness is that birds have magnetoreceptors in their heads to sense the earth's magnetic field for orientation and navigation (Wu and Dickman 2012), and magnetism is closely related to superconductivity.

A simpler conjecture is that consciousness is a matter of passing a critical threshold for some quantity, perhaps the number of neurons or ribosomes or other important molecules such as DHA. Any or all of these could contribute to a phase transition, either to a phase like superconductivity mentioned above or to some new physical phase as yet unknown. A set of changing states of consciousness could form a path in a phase diagram crossing various critical boundaries.

In summary, the brain may be both simpler and more complicated than we thought: Simpler because fundamental units of computation may be ribosomes and proteins, which are much more understandable than neurons. But more complicated because

[2] Many thanks to C. Prescod-Weinstein for this reference

the combined computational power of ribosomes and proteins in the brain is orders of magnitude more than we previously thought. We still do not know what virtual software a brain or a neuron is running, but we may get closer by thinking in terms of active information machines. There is hope for the compatibility between higher-level virtual machines and a multitude of nanoscale machines, because "Animals and humans offer an existence proof that current insuperable difficulties can, somehow, be dissolved" (Boden 2008).

Changing our point of view and seeing ribosomes as machines that convert information to active material, and seeing brains as doing more than just pure information-processing–these could all lead to a deeper understanding of our computing machinery, both biological and non-biological. Understanding ribosomes better should help us fathom both life and mind, and constructing artificial ribosomes could make both artificial life and AI possible (Orelle et al 2015). Or at least Turing's main point in his 1950 article, "that AI could (at least) simulate intelligence" (Turing 1950, Boden 2006).

To reach this goal, however, we will need to recognize that intelligence is inseparable from action, and to come up with a new version of Turing's Imitation Game that captures both information processing and action.

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