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# Opening Statement: What is Computation?

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**Most people understand a computation as a process evoked when a computational agent acts on its inputs under the control of an algorithm. The classical Turing machine model has long served as the fundamental reference model because an appropriate Turing machine can simulate every other computational model known. The Turing model is a good abstraction for most digital computers because the number of steps to execute a Turing machine algorithm is predictive of the running time of the computation on a digital computer. However, the Turing model is not as well matched for the natural, interactive, and continuous information processes frequently encountered today. Other models whose structures more closely match the information processes involved give better predictions of running time and space. Models based on transforming representations may be useful.**

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## 1. INTRODUCTION

The question before us – “what is computation?” – is at least as old as computer science. It is one of those questions that will never be fully settled because new discoveries and maturing understandings constantly lead to new insights and questions about existing models. It is like the fundamental questions in other fields—for example, “what is life?” in biology and “what are the fundamental forces?” in physics—that will never be fully resolved. Engaging with the question is more valuable than finding a definitive answer.

This symposium is an exploration of the computation question by many observers. To get the discussion going, I (as Ubiquity editor) have composed this opening statement. I do not intend this as a definitive answer, but as a reflection to stimulate commentary and reactions. The commentators may not agree with everything in this opening statement or with what the other commentators have to say. Our hope is that readers will gain a greater appreciation of pervasiveness of computation and the value of the ongoing exploration of the nature of computation.

## 2. WHY NOW?

Why take up this question now? There are several reasons, in addition to the opportunity to address this question on the occasion of the centenary of Alan Turing’s birth.

It was selected as the most important question facing our field by over one hundred of the two hundred participants in the Rebooting Computing Summit of January 2009 (<http://rebootingcomputing.org>). They were trying to come to grips with the identity of the computing field as they worked to attract young people and collaborate with others in other fields.

It addresses the issue of our core identity, which has been under stress in the past decade because of job growth, outsourcing, expansion in the number of fields affected by computing, and internal tensions between various elements of the computing field.

Many of us desire to be accepted as peers at the “table of science” and the “table of engineering”. Our current answers to this question are apparently not sufficiently compelling for us to be accepted at those tables.

We need to respond to friends and colleagues in other fields who are discovering new natural computational processes. They look to us for insights in how the processes work, what algorithms might be behind them, and how we might collaborate to discover more.

The term “computational thinking” has recently become popular [1], after hibernating many years in the jargon of our field. We are discovering that neither we in the field nor our friends outside agree on what this term means. Future education and research policies depend on the answer. We need a better answer.

### 3. HISTORY OF THE TERM COMPUTATION

Our review of the history of computer science reveals an interesting progression of definitions for computer science [2]:

- study of automatic computing (1940s)
- study of information processing (1950s)
- study of phenomena surrounding computers (1960s)
- study of what can be automated (1970s)
- study of computation (1980s)
- study of information processes, both natural and artificial (2000s)

Over time, the definition of computer science has been a moving target. These stages reflect increasingly sophisticated understandings of computation.

In the 1930s, Kurt Gödel [3], Alonzo Church [4], Emil Post [5], and Alan Turing [6] independently gave us the first definitions of computation. Gödel defined it in terms of the evaluations of recursive functions. Church defined it in terms of the evaluations of “lambda expressions”, a general notation for functions. Post defined it as series of strings successively rewritten according to a given rule set. Turing defined it the sequence of states of an abstract machine with a control unit and a tape (the Turing machine). Influenced by Gödel’s incompleteness theorems, Church, Turing, and Post discovered functions that could not be evaluated by algorithms in their systems (undecidable problems). Church and Turing both speculated that any effective procedure could be represented within their systems (the Church-Turing thesis). These definitions underlay the earliest formal notions of computing.

In the time that these men wrote, the terms “computation” and “computers” were already in common use, but with different connotations from today. Computation meant the mechanical steps followed to evaluate mathematical functions. Computers were people who did computations. In recognition of the social changes they were ushering in, the designers of the first digital computer projects all named their systems with acronyms ending in “-AC”, meaning automatic computer-resulting in names such as ENIAC, UNIVAC, and EDSAC.

The standard formal definition of computation, repeated in all the major textbooks, derives from these early ideas. Computation is defined as the execution sequences of halting Turing machines (or their equivalents). An execution sequence is the sequence of total configurations of the machine, including states of memory and control unit. The restriction to halting machines is there because algorithms were intended to implement functions: a nonterminating execution sequence would correspond to an algorithm trying to compute an undefined value.

The famous ACM Curriculum 1968 [7] was the first curriculum recommendation in computer science. It translated these formal definitions into practice by defining computation as information processes generated by algorithms. They said

the field consists of three main parts: information structures and processes, information processing systems, and methodologies.

Around 1970, Edsger Dijkstra began to distinguish algorithms from computations. An algorithm, he said, is a static description, a computation the dynamic state sequence evoked from a machine by an algorithm. The computation is the actual work. He wanted to constrain the structure of algorithms so that the correctness of their computations could more easily be proved. With this he launched the structured programming movement.

The computer science formalists were not the only ones interested in a mathematical definition of computation. In the OS (operating systems) world, the process (short for computational process) became a central concern [8–10]. A process was intended as an entity containing the execution of an algorithm on a machine. Dennis and Van Horn defined a process as “locus of control through an instruction sequence” [8]. Coffman, Denning, and Organick defined process as the sequence of states of processor and memory for a program in execution [10,11]. The process abstraction enabled time-sharing: processes could be suspended from the processor and resumed later. The OS interpretation of process differed from the formal interpretation in one key point: An OS process could be intentionally nonterminating.

During the 1960s there was considerable debate on the definition of computer science. Many were concerned that the formal definition of computation was too restrictive; for example, the new field of artificial intelligence was not obviously computational. Newell, Simon, and Perlis proposed to remedy this by broadening to include all “phenomena surrounding computers” [12,13]. At the same time, many were also concerned about whether the word science in the title was deserved. Economics Nobel Laureate Herb Simon claimed that some fields of study, such as economics and computer science, are sciences even though they did not study natural processes [14]. Because they encompassed new phenomena that most people considered computational, these new definitions were widely accepted. This was a fundamental shift in the understanding of computation, which now became pegged to the activities in and around computers rather than to the presumed algorithmic nature of information processes.

A few years later, the COSERS project team, led by Bruce Arden, tied the definition of computation to a concern for automation [15]. This connected computation even more firmly to the actions of machines.

In the mid and late 1980s, the computational science movement, which was backed by scientists from many fields, claimed computation (and computational thinking) as a new way of doing science [16,17]. Supercomputers were their main tools. But now computation was more than the activity of machines; it was a practice of discovery and a way of thinking.

Finally, in the 1990s, scientists from natural science fields started to claim that information processes exist in their deep structures [18]. David Baltimore argued this for biology [19]

and those working on quantum computing argued it for physics [20]. Today, computation is seen as a natural process as well as an artificial one. This is a serious challenge to the tradition of definitions tying computation to computers.

#### 4. NEW DEVELOPMENTS

Since the basic definition of computation was established, there have been three significant developments that call for rethinking the basic reference model. All three indicate classes of processes that most people agree are computations, but which do not fit the form of the basic Turing machine.

**Interactive computing.** Many systems, such as operating systems, Web servers, and the Internet itself, are designed to run indefinitely and not halt. Halting is an abnormal event for these systems. The traditional definition of computation is tied to algorithms, which halt. Execution sequences of machines running indefinitely seem to violate the definition. Goldin, Smolka, and Wegner [21] assembled a book of 18 contributions by authors who thought interactive computing to be computation, even though it didn't fit the standard formal definition. The term "reactive system" is often used for a system that continues its operation indefinitely and responds to stimuli from the environment. A proposed solution to the definition problem is to expand the definition to include reactive systems as well as algorithmic computing machines. (I personally prefer the term "interactive system" to "reactive system" because interactive also allows the system to generate output signals and not just react to incoming signals.)

In discussing games, James Carse said: "A finite game is played for the purpose of winning, an infinite game for the purpose of continuing the play." [22] When applied to our situation, his insight highlights the fundamental difference between computations and algorithms (they are finite games) and computations from nonterminating systems (they are infinite games).

**Natural information processes.** Leading thinkers in various science fields have declared that they have discovered information processes in nature. The most conspicuous of these claims is in Biology, where DNA is seen as an encoded representation of a living organism and DNA translation is an information process that transforms the code into amino acids [19]. Similar claims are coming from physicists who see natural information processes behind quantum mechanics and other natural phenomena. Perhaps the most sweeping version of this claim is Wolfram's [23]; he believes that all of nature is an information process (best described by cellular automata) even though we do not know (or may never know) the algorithms that generate natural processes. Computer science has been challenged to redefine computation in a way that accommodates these discoveries.

**Continuous information processes.** Turing machines are discrete entities that work with finite strings of symbols from a finite alphabet. This definition excludes analog computing, which was very important in the 1920s and continues in some electrical engineering specialties today. In the 1920s, Vannevar Bush developed the differential analyzer, a machine of gears, levers, and rotating shafts that could solve differential equations. Electrical engineers developed their own versions of analog differential equation solvers; these technologies are still in use today. Why is solving a differential equation on a supercomputer a computation but solving the same equation with an electrical network is not?

Turing himself argued that in the real world measurement error limits the granularity at which we can observe continuous processes; therefore there is no practical difference between what discrete and continuous machines can compute. Others are not so sure because a simple roundoff error in the machine can cause its prediction of a continuous function to err significantly.

The mathematical models (such as partial differential equations) used in science and engineering assume continuous functions on real numbers. Many optimal algorithms for making predictions with these models are formulated without reference to a Turing model and lead to more accurate predictions of computational work than can be obtained from a Turing model of the same solution method [24].

Claude Shannon (a student of Bush) said that continuous signals contain information and that his information theory applies to all such signals [25]; he focused on discrete (binary) signals because they were the coming wave in communication systems. Today we use his information theory for discrete computing but ignore it for continuous information signals. Software radios today use signal processing algorithms to sample and decode radio signals. Why is the action of a software radio a computation but not the action of an Armstrong FM circuit? Paolo Rocchi (IBM, Rome Italy) has just completed a book showing that there is no clear boundary between analog and digital computation [26]. He challenges us to define computation in a way that encompasses both.

#### 5. RETHINKING THE DEFINITION

Computation is always defined relative to a computational model that specifies the agent performing the computation. Computation is seen as a process generated by that agent. Any of the four computational models proposed in the 1930s – recursive functions, rewriting rules, lambda-calculus, and Turing machine – could have been used as the reference model for computation. The Turing machine won that designation because it most closely resembled the new generation of digital electronic computers.

Over the years, new computational models were proposed including probabilistic machines, non-deterministic machines, parallel program schemata, Petri Nets, neural networks, DNA

string systems, and others. Every one of these systems was found to be Turing equivalent. This bolstered belief in the Church-Turing thesis and reaffirmed the reference model status of the Turing machine.

So, what is the problem with the Turing model? To many, the Turing machine model is a poor representation of the systems they are interested in. For example, a DNA molecule being transcribed does not resemble a moveable control unit on an infinite tape. The theorems about running times of algorithms on Turing machines do not help mathematicians solving continuous models predict the running times of their models.

Suppose that we dropped our insistence that the Turing model is the unique basis of computation? That would mean not only that we could use Turing-equivalent models that more clearly fit the domains we are studying, but also that we could get more accurate predictions of computational work in those domains than we could with Turing machine models. We would have more options for designing near-optimal methods for solving problems.

## 6. A TRANSFORMATION OF REPRESENTATIONS MODEL

Let us consider an alternative based on a model of information process that may be useful when the computations appear to be strings or streams, such as in DNA translation, genetic algorithms, and analog computing.

A representation is a pattern of symbols that stands for something. The association between a representation and what it stands for can be recorded as a link in a table or database or as a memory in people's brains. There are two important aspects of representations: syntax and stuff. Syntax is the rules for constructing patterns; it allows us to distinguish patterns that stand for something from patterns that do not. Stuff is measurable physical states of the world that hold representations, usually in media or signals. Put these two together and we can build machines that can detect when a valid pattern is present.

Even this simple notion of a representation has deep consequences. For example, there is no algorithm for finding the shortest possible representation of something [27].

Unfortunately, information processes can be treacherous territory, because "information" is such an ill-defined and conflicted term, despite many efforts to establish international standards for its definition. Most definitions of information involve an objective component (signs and the things represented by signs) and a subjective component (the meanings). Rocchi says that information consists of a sign (representation), a referent (the thing represented), and an observer [26]. The objective parts of information are in the signs and referents, while the subjective part is in the observer. How can we base a scientific field on something with such a strong subjective component?

Biologists have a similar problem with life. Life scientist Robert Hazen notes that biologists have no precise definition of life, but they do have a list of seven criteria for when an entity is living [28]. The observable affects of life, such as chemistry, energy, and reproduction, are sufficient to ground the science of biology. In the same way, we can ground a science of information on the observable affects (signs and referents) without a precise definition of "meaning".

Despite these cautions, representation-transformation can be a reference model of computing. An information process is a sequence of representations. (In the physical world, it is a continuously evolving, changing representation.) A computation is an information process in which the transitions from one element of the sequence to the next are controlled by a representation. (In the continuous world, we would say that each infinitesimal time and space step is controlled by a representation.)

The representation-transformation model does not enlarge the class of functions that can be computed; representations and their representation-controlled transformations are Turing-equivalent. Its value is as a model of computations that naturally describes not only the traditional processes of computing machines, but also non-terminating processes, natural processes, and continuous processes.

## 7. EXAMPLES

Let us examine a quick series of examples as sanity checks that this definition can work for the cases we described earlier.

The sequence of configurations of a Turing machine is obviously a computation in this interpretation.

The non-terminating, interactive processes of operating systems and the Web are also clearly computations in this interpretation.

DNA translation is a natural information process. The DNA is taken as "genetic code" and is composed of long strings made up of four types of base pairs. DNA translation is a rule-based process that "reads" the code and produces amino acids. Douglas Hofstadter was one of the first to notice that DNA transcription can be interpreted as a Turing-machine like process [29].

Quantum computing represents information as "qubits" (superpositions of the "0" and "1" states of a bit) and quantum algorithms as methods of transforming qubits. In some cases, such as factoring with Schor's algorithm, a quantum computer can solve problems in polynomial time that would take exponential time on conventional computers.

Science problems represented as continuous mathematical models operating with real numbers are continuous information processes.

## 8. CONCLUSIONS

The computational model of representation-transformation refocuses the definition of computation from computers to

information processes. This model shows that representations are more fundamental than computers because representations appear in many situations where no computer is present.

This is actually a fundamental shift. It relinquishes the early idea that “computer science is the study of phenomena surrounding computers” and emphasizes that “computer science is the study of information processes”. Computers are a means to implement some information processes. But not all information processes are implemented by computers—for example, DNA translation, quantum information, optimal methods for continuous systems. Getting computers out of the central focus may seem hard but is natural. Dijkstra once said, “Computer science is no more about computers than astronomy is about telescopes”.

Are algorithms really the heart of computing? Or is the more fundamental and inclusive notion of representations the heart? Science is discovering information processes for which no algorithm is known; might some of those information processes have no algorithms at all?

This model does not resolve the tortured question of “what is information?” It deals with the objective parts of information (representations and the mappings to their referents) and but does not depend on the subjective aspect of information (the individual observer). We can proceed without solving the observer problem.

This definition of computation also supports a clear definition of computational thinking. Computational thinking is an approach to problem solving that represents the problem as an information process relative to a computational model (which may have to be invented or discovered) and seeks an algorithmic solution. The pioneers of our field used the term “algorithmic thinking” to describe how the thought processes of computer scientists differ from other sciences [13]. In the 1980s, the term “computational thinking” was commonly used to describe the way that computational scientists approached problem solving, which they characterized as a new paradigm of science [30]. I am concerned, however, that the conception of computational thinking as a method of problem solving may sound too close to Polya [31] and may not call sufficient attention the aspects that make computing unique in the world [32].

We have been too willing in our field to embrace major terms without clear definitions (for example, software engineering, structured programming, and cloud computing). When we do not explicitly declare that we are on a quest for a clearer definition, we allow others (and ourselves) to think we are satisfied with the imprecision. This is a paradox because our field demands great precision—the smallest error in a representation can invalidate all subsequent results. It surprises me that we do not collectively demand more precision in the words we use to describe who we are and what we do. I am hoping that this symposium will help us to accomplish that with one of our most fundamental notions.

## ABOUT THE AUTHOR

Peter J. Denning is Director of the Cebrowski Institute for innovation and information Superiority at the Naval Postgraduate School in Monterey, California, and is a past president of ACM. He is currently the Editor-in-Chief of ACM’s on-line journal Ubiquity. Peter is widely known for developing the *Principle of Locality* which has been very effectively utilised for organising cost-effective memory access, as in virtual memory systems where he also invented the concept of *Working Sets*, and also for organising computations in a spatially effective way to avoid excess communications.

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