Chapter 1

Welcome to Computer Science

Computer science, of course, is the science of computers. But what is that?

1.1 Science

A kind of thing that exists in the natural world is called a natural kind, where the word thing is used in a broad sense to include not only kinds of objects but also kinds of materials, processes, forces, relationships etc. For example, blue jays (cyanocitta cristata) constitute a natural kind in the realm of biology; gravitational forces constitute a natural kind in the realm of physics, and platinum is a natural kind studied in the field of chemistry.

Classifying the things of the world into kinds is not easy. A bird and a bat, for example, meet our immediate, naive experience as being more similar than a whale and a bat. In obvious ways, of course, the bird and the bat are more similar. But in some ways the whale and the bat are more similar and these are deep similarities – that is, they are key in understanding or predicting other (perhaps hidden) similarities of interest. Classifying the things of the natural world into kinds according to their deep similarities is one of the tasks of science, and in fact its foundation.

As a second example, looking up into the night sky there is an obvious difference between the large light of the moon on one hand, and numerous smaller lights on the other. If one watches long and close, however, it may be noticed that most of the lights move along the same path every night, but a few (five, not counting the moon) move along paths which change slightly from one night to the next – gradually shifting course over periods of weeks and months. This deep difference in kind, between the fixed and wandering lights of the night sky, was recorded with careful attention by the ancient Sumerians around 3000 BC – though they did not realize that these “wandering lights” really gave off no light of their own, or that there were three more hidden deep in the sky, or that they were standing on one of them.
While the wandering of planetary motions was observed at least five thousand years ago, the particular paths they took were a source of mystery and wonder for practically all of that time. It was not until the early 1600's that the German Johannes Kepler (1571-1630) made sense of these motions by giving a simple formula for the paths along which the planets moved. Today we put things in space orbits and use Kepler's formula to know the paths they will take, but Kepler himself had no such plans; he simply wanted to understand what he saw. What Kepler was searching for, and found, was a law of nature: a fundamental principle that governs naturally in the world.

Generally speaking, a truth is fundamental if, or to the extent that, it can be used to explain or infer other truths of interest. In the case of Kepler's laws these truths of interest were the paths taken by orbiting bodies in general, and the known planets in particular. It happened that around the same time Italian Galileo Galilei (1564-1642) discovered a formula for the paths of objects tossed through the air here on Earth, from a wad of spit to a cannon ball; so Galileo's theory, though of a different realm, was fundamental in the same sense as Kepler's. Toward the end of the same century Englishman Isaac Newton (1642-1727) would find a common pattern behind both Kepler's and Galileo's formulas in terms of general principles of gravity and motion, so that objects in space and near the Earth were now known to obey just the same laws. Newton's theory was yet more fundamental than those of his continental forebears — though he gave them much of the credit, once writing, "If I have seen further it is only by standing on the shoulders of giants".

We can now say that the goal of science is to discover the deep similarities and fundamental truths of that natural world – or, in slightly more technical terms, to reveal the kinds and laws of nature. Not just any activity with this aim, however, seems to count as science. If someone were to conduct an investigation into the kinds and laws of nature, say, by use of a Ouija board, there is an important sense in which they would not be doing the same thing as Kepler, Galileo, or Newton. A non-scientist might guess that this is because Ouija boards are not part of "the scientific method", but this is not the issue. If the methods we use today are improved upon substantially by the coming generation (as I hope they will be), they will not necessarily then say that they are doing something besides science, or that we were — even though they may use methods different from ours. So there is no such thing as the scientific method. The issue with the Ouija board is not that it is against the rules of some game; it is that the Ouija board is a game, and using it to try to reveal the laws of nature would be irrational.

What does it mean to be believe rationally? The American Heritage Dictionary, 3'rd ed., defines rational, in the relevant sense, as having or

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1 Isaac Newton, in a letter to Robert Hooke, February 1676.
2 ©Hasbro Games Inc.
exercising the ability to reason; but it defines to reason as the capacity for logical, rational, and analytic thought – so the dictionary does not really unwind the issue here. However, if one watches how people use the words rational and reason, a pattern emerges that includes more than their merely being used alongside one another: we say that a belief is rational if it is acquired through methods that tend reliably to reveal the truth, and rational judgment is called reasoning.

At this point one might ask who's to say what is the truth, or what methods tend to reliably reveal it. This is an important question, and a very natural one. It is in a certain grain of human nature to suppose that if there is an issue to be settled, then someone must have authority to rule on it. In fact this is why, historically, it took so long for science to even begin. Scientific thought goes against this grain of human nature by taking the stance that the truth is the truth, and while no one has authority to rule on it, each of us is endowed with faculties to seek it out – viz., the faculties of reason. Thus it is the job of a scientist not to make rulings on the truth, but to show evidence that enables his audience to judge rationally for themselves. This principle is enshrined in the motto of The Royal Society as nullius in verba, or nothing on the word (of authority).

Reasoning that does not rest on any supposed authority is said to be independent, and the expectation of independent reasoning on the part of an audience is what sets science apart from witch doctoring. A witch doctor says “Listen to me; I have a special power to read the signs.” A scientist says “Don't listen to me. Here is the evidence; see for yourself”. If she gives you a purported theorem, she gives you a proof of that theorem which, with enough effort, you can read as well as she can. If she gives you a purported experimental result, she gives you a description of the experiment and its analysis in enough detail and clarity that you may critique it or repeat it, and she welcomes you to do either. A great scientist like Kepler, Galileo, or Newton may know better than most of us where to look for certain answers, but if we trace their footsteps (or thought-steps) and look there ourselves, then we can see the same things, nullius in verba. With this in mind we can define science, in summary, as the effort to reveal the kinds and laws of nature to the faculties of independent reason.

If the expectation of independent reasoning seems like common sense, it is only because of the revolutionary influence of scientific thought and the values that gave it birth. In many times and places it has simply not been thought of to challenge the assertions laid down by authority. Aristotle (wrongly) wrote that heavy objects in general fall faster than light ones, and there is no record of it being doubted until the time of Galileo two thousand years later. Galileo himself spent the last years of his life under a sentence of house arrest for refusing to recant his assertion that the Earth revolved around the Sun – a
matter which had been ruled upon by the Sacred Congregation of the Index in 1616. If anyone seemed crazy at the time it was Galileo, for his steadfast defiance if not his position on astronomy. If you have ever felt intimidated into holding your tongue on a rationally defensible point of fact, then you have felt forces which at times held terrifying sway over the thoughts of people and nations, and at times still do. The opposite should not be taken for granted.

1.2 Engineering

Some people do not care to distinguish between science, engineering, and technology. They imagine, more or less, a vast network of "smart people" behind a mysterious curtain. They slide money to us underneath the curtain, and we occasionally toss gizmos back over the top. Of course this is a naive way of looking at the situation, and at least those of us on this side of the curtain should have a clearer picture of what is going on.

We have already noted that Kepler's aim, consistent with that of science in general, was to understand the laws of nature. So was Galileo's and so was Newton's. It is not likely that Newton, on the day after discovering the laws which govern the motions of objects in the universe, would have knocked on the door of a wagon wheel maker and said, "Hey, guess what...". Yet today there is scarcely a factory or foundry in the world (even one that makes wheels) whose operation does not depend in a critical way on the knowledge of Newton's discoveries. The point is that these things take time. They also take expertise, specifically in the field of engineering. Engineering is the application of scientific knowledge to the design of technology.

Behind the curtain, so to speak, it is not clear in principle how science would relate to technology — since science considers kinds and laws of nature while technology is, by definition, created by humans through our own plans and for our own purposes. To see how science might come into it let us consider, for example, a truck.

A truck is an artifact, that is, a man-made thing, and not a member of any natural kind. We can build it however we like and its behavior will depend, in some respect, on each decision we make in the process. The critical fact, however, is that once the truck is designed and built through the sequence of choices we make, on the last move of the game it is always nature's turn. The ways in which the artifact's performance depend on its design are unchanging and beyond our control; those truths are truths of nature.

Now while it behaves according to laws not of our making, a truck itself is not a subject of science — because the design of a particular model of truck, however valuable, is of only temporary and specific interest, and hence not fundamental. The behavior of the truck, however, depends on the behaviors of its elementary components such as gears, springs, and pistons; and while its
overall design may have a short life, our need to understand the workings of these basic components is both general and enduring. That is, such knowledge is fundamental in just the way a natural law must be. So in science texts one reads not only of things like blue jays and nimbus clouds, but also of things like springs and electrical resistors.

Our basic formula for the workings of a truck’s valve springs, for example, is due to investigations conducted by Robert Hooke (1635-1703, to whom Newton wrote, “...on the shoulders of giants”). Naturally, Hooke did not have valve springs in mind. In fact his curiosity need not have been limited to so-called springs at all. A tree blowing in the wind obeys the same law as a metal coiled spring – just as a tree struck by lightning follows the same law as a manufactured resistor. The laws governing basic technological components would in most cases be of interest even if we did not build machines out of them.

It has been mentioned that the performance of a truck, for example, depends on the behaviors of its simple parts. However, the truck’s performance depends not only on that, since there is also the matter of how the parts are arranged and connected in the final product, and the process by which they get to be arranged and connected in that way. These aspects of truck-design are outside the purview of science, and so engineering requires knowledge of the relevant science together with the skills needed to apply this science to the design of technologies of a given sort.

The key distinction here is not between scientists and engineers as separate people, but between science and engineering as separate activities. Some people concentrate chiefly on one; some people concentrate chiefly on the other, and some people switch back and forth. About five years after discovering the law of springs, Hooke used it to develop a pocket watch that kept accurate time, which was the first of its kind. When Hooke was investigating the laws of elastic tension he was working as a scientist, and once he succeeded he knew that things which are stretched behave in a certain mathematical way. When he used these laws to design the watch he was working as an engineer, and once he succeeded he knew how to build the watch.

The boundary between science and engineering can be subtle, but if we are engaged in either one then we should do our best to understand which. This is because if the two are blurred, then the dependency of engineering on science is equally blurred, and so is the importance of science to the people on the other side of the curtain. Scientists, when they are really doing science, are seldom the ones handing over the gizmos.
1.3 Technology

Anthropologists define technology as the body of knowledge available to a civilization that is of use in fashioning implements, practicing manual arts and skills, and extracting or collecting materials\(^3\). Someone who is an expert in the use, maintenance, or manufacture of technology is said to be a technician. A technician needs to understand existing technology but need not be in the business of inventing new technology – just as an engineer needs to understand existing science but need not be in the business of making scientific discoveries.

Hooke’s pocket watch is an example of engineered material technology, which is stereotypical in most peoples’ minds; but not all technology consists in the knowledge of how to design things. The knowledge of how to tie a square knot, how to to perform CPR, or how to to train a seeing-eye dog, are all examples of non-material technologies.

Moreover, not all technology requires science. The Ancient Phoenecians were able to build marvelous ocean-going ships through a craft which, while highly sophisticated, did not bring to bear anything that could rightly be called science. There is nothing wrong with not using science, and it should not be seen as a cure-all or an indispensible ingredient. Give me a fast ship any day over one with “more engineering”.

Technology can have impact in two ways. Some technologies, such as electric lighting, have impact directly benefiting their users. Others, such as the cotton gin, the deisel tractor, or the steamship, have impact because they decrease the cost of manufacturing or delivering other things. Inventions of the latter sort, when they impact a large segment of the economy, can be the ones that make epochs in history.

For example, the plough and harness enabled the transition to bona fide agriculture from hunting, gathering, and horticulture. This increase in efficiency meant that for the first time, people had energy left over after securing food and shelter to do other substantial things – such as writing, exploration, and monumental architecture. Millenia later the results of such exploration and writing were made widely available through the inventions of printing and movable type, enabling the Reformation and the Renaissance.

A broad based transition from agriculture to industry began in England around 1800. Nobel Prize winning economist Robert Lucas Jr. wrote of this transition that “For the first time in history, the living standards of the masses of ordinary people have begun to undergo sustained growth...Nothing remotely like this economic behavior has happened before”. The transformation was push-started by three key technologies: steam power, the mechanized cotton spinner, and improvements in the smelting and working of iron. Few people laid hands on all three of these technologies, but vast numbers benefited through

\(^3\)American Heritage Dictionary, third edition
trade. The pace of industry was eventually pushed to new levels by material technologies such as rail travel – and also by advances in the methods and processes of production, or operations management, including assembly lines and standardized parts.

1.4 Computing

At the mention of the word “computer”, most people think of a certain sort of appliance. It would be strange, however, if these appliances were the subject of computer science. Branches of science are not normally named after appliances, or in general after sorts of artifacts. Universities have no departments of “bicycle science” or “flashlight science” (though science is at work in the designs of modern bicycles and flashlights). Even what lay people call “rocket science” is called aerospace engineering by the people who actually do it.

The word “compute” appeared in English around 1400, from the Latin computāre. The word “computer” is derived from “compute” in the same way that “runner” is derived from “run”, and so that word is potentially just as old, and in any case much older than the appliances we now associate with it. Computing, in the first and most general sense, is processing data according to an algorithm. Whatever does this is a computer and hence subject to the laws of computer science; but now the need is raised to define two other things.

1.4.1 Data

A collection of patterns is discrete if patterns within the collection can be clearly identified and distinguished. For example, the letters of the alphabet form a discrete set, since we can normally tell which letter we are looking at, and also tell one from another. Discrete collections, such as the alphabet, have the property that a range of physically different patterns are identical for their intended purpose. For example while one printed token of the letter ‘e’ may be larger or smaller than another, or written in a different font, they are the same pattern for their intended purpose (usually to form the words of a message). A discrete collection of patterns is called a data space, and a pattern within a data space is called a datum (plural: data).

Of course it is possible to create a would-be letter that cannot be clearly identified, for example as to whether it is supposed to be an ‘r’ or an ‘n’; but it is also possible, without too much difficulty, to write letters that can be clearly identified, and this is what counts for discreteness. The possible configurations of magnetism of an old fashioned video tape, or ridges and valleys in the groove of a vinyl record, by contrast are not discrete. Two such patterns that differ physically will have correspondingly different effects on the systems that read
them (in this case, by a video or record player), whether those differences be large or small.

1.4.2 Algorithms

A state of a system is a way that system can be. For example, the state of a game of billiards at any given moment might be described in terms of the positions and velocities of the balls on the table, whose turn it is, the score of the game, etc. A process taking states within a data space is called a data process. As noted above, the states of a data process are multiply realizable, which is to say that physically different patterns may be identified as the same state.

An algorithm is a collection of rules that either govern a data process, or are intended to. A game of tic-tac-toe, for example, can be viewed as a data process whose states are the possible configurations of x’s and o’s on the board and whose algorithm is given by the rules of tic-tac-toe. When viewed in this way the game is subject to the laws of computer science. The same game could also be viewed as a physical process subject to the laws of physics, or an interactive cognitive (that is, thought) process subject to the laws of psychology. How we view the system and which laws we apply is a matter of our interests in it. If, for example, our interest is in strategies for winning at tic-tac-toe (that do not involve intimidation or other psychological maneuvering), then the appropriate perspective is computational.

Note that tic-tac-toe proceeds in accordance with rules which determine what is or is not a legal move, but these rules do not completely determine the succession of states in the game. A data process, such as tic-tac-toe, that can proceed in different ways from the same starting state is said to be nondeterministic. Naturally, a data process that is not nondeterministic is said to be deterministic.

1.4.3 Modeling

We have noted that certain games are a form of computing technology, and they are one of the oldest forms. It was at least five thousand years ago when people began pushing tokens and tokens and symbols around, according to rules, for competition and enjoyment. But people also discovered that they could manipulate tokens or symbols by a different set of rules to predict, say, how many people could be fed, and for how long, from a certain field of wheat. We often take this sort of calculation for granted but from a certain perspective it is miraculous: at some level, the concept behind a Ouija board is not altogether off – it just depends on careful choices about the rules of the game and the predictions it is used to make.
1.4. COMPUTING

A model of a process or object is something which corresponds with it systematically in certain respects of interest. A scale model of an object, for example, corresponds to it with respect to the proportions of its various measurements. For example if a certain truck is four times as long as it is wide then a scale model of the truck will be also. If a model of a certain tunnel is built to the same scale, then we can predict whether the truck fits through the tunnel by seeing if the model truck fits through the model tunnel; and this may be a less expensive experiment, especially if the answer is no.

A mathematical object which is a model of something is called a mathematical model of that thing. Mathematical objects will be considered in depth in Chapter 3, but for now it suffices to say that they are abstract, nonphysical objects, and that consequently a mathematical model of something is of a different nature than, say, a scale model. In particular mathematical models do not look like the things or processes they correspond with. Nevertheless they can be used to predict certain aspects of behavior of those things or processes, as for example in calculating the expected yield of a field of grain. The extraction of predictive or explanatory information from mathematical models is done through computation, and this is the primary basis of peoples' historical interest in computing, so-called (that is, aside from recreational games).

1.4.4 Computer Science

Algorithms used in modern computing can be quite complex. The algorithms that guide a Tomahawk cruise missile, for example, take over 1.5 million lines to write down in machine-readable form\(^4\). As with other sorts of artifacts, however, certain elementary components are of fundamental importance in the construction of a wide range of algorithms. These elementary components correspond to certain mathematical functions such as those of arithmetic and numerical processing, sorting, searching, solving, and parsing (all to be covered in later chapters). The algorithms that realize, or implement these functions are the springs and levers of computing, and the laws describing their behavior are the computer science analog of Hooke's law of springs, or Archimedes's law of levers. More fundamental laws of computer science are those governing certain general categories of algorithms, and we will take up some of those as well. The question of whether there are laws that govern all computation, and if so whether and how we could discover them, is a deep one and will be discussed in Chapter 6. The short answer is that there are and we can – but why should you take my word for it?

1.5 Conclusion

The wealthiest person in history, as of this writing, made money not in weapons, fuel, food or medicine, but in software (software is simply an algorithm that can be executed by a machine). This is of little wonder: the product his company makes costs practically nothing to manufacture and distribute, is as valuable to consumers as a piece of furniture, and is used by most people in the industrialized world. It should not be thought that these people are being cheated; though the product is a bit clunky, they traded for it willingly and without misinformation. What is at work here is the effort-amplifying effects of software as a product. The only real cost of delivering software is the cost of figuring out how to make it do what it is supposed to. Once that is accomplished the software itself can be produced and delivered on a wide scale at negligible cost. Whether one wants to pocket the wealth they create like Bill Gates, or give it away like Linus Torvalds or Tim Berners Lee, there has never in history been a way to deliver so much value, to so many people, through a localized or individualized effort, as by writing software.

It was noted in Section 1.3 that epochal transitions in history often hinge on technologies that streamline the production or delivery of goods in a wide segment of the economy. As this is written we are on the cusp of such a transition. Digital computers, electronic documents, the internet, and the World Wide Web, have driven the marginal cost of duplicating and distributing information to near zero; and this includes algorithmic information that performs major tasks in our lives. Information is the largest single segment of the modern economy; and the infrastructure through which information is copied and transmitted today makes the printing press look like a clay tablet and the railroad look like a rickshaw.

On a historical scale we have only caught glimpses of the effect. It is difficult to see the boundaries of epochs when they are standing on them. The invention of the gun, for example, transformed the way wars were fought quite thoroughly, but not at all quickly. In fact guns had little effect in their first few centuries as their speed, reliability, and usability caught up to potential. Electronic computers have already had many times more impact on the battlefield than guns had during a comparable period after their invention. This was the only use of guns at the time; it is far from the only use of computers.

As with early guns, however, algorithms produced today often behave in unplanned ways that are inconvenient, or even harmful, to their users or others who depend on them. Writing secure, reliable software is one of the most difficult intellectual tasks ever attempted by humans. It is, to borrow a phrase from computer science pioneer Edsger Dijkstra, cruelly hard. At the same time every success we make in this direction creates value at a speed and scale unprecedented in the history of technology.
1.5. CONCLUSION

It is not always the case, however, that technological problems are solved by paying them direct attention. A *Nimitz*-class aircraft carrier, for example, weighs over 130,000 tons and can run for 20 years, at speeds of up to 30 knots\(^5\), without refueling. The key discovery enabling the design of such a ship was the equivalence of matter and energy, made by Albert Einstein in 1905. The other discoveries and inventions that lead from Einstein's law to the development of nuclear power, however, were unforeseeable at that time. If in 1905 Einstein himself had been recruited to study power engineering, instead of trying to understand the nature of matter and energy, the eventual development of such a power plant might have been delayed by just as many years as Einstein spent on it. More generally if all our thoughts went into improving technology, without a natural curiosity about how the world works and the aid of discoveries we make for just that sake, I believe we might still be hunting birds with bows and arrows for our evening supper. (Bloody nice bows and arrows, though.)

It would be naïve to think that computer science, in the strict sense as pioneered by the likes of Alonzo Church, Alan Turing, Stephen Cook, and Tony Hoare, is over. Discoveries remain to be made that will change the way we think about algorithms, and how we represent and reason about them, at a a fundamental level. It may also be that a game changing advance in the reliability and effectiveness of software will *require* such a discovery, in the same way that the invention of the repeating firearm required the discovery of nitric acid, and the invention of nuclear power required the discovery of the equivalence of matter and energy. Such a breakthrough in the field of computer science at this point in history could be among the most technologically enabling discoveries ever made. That is one reason I am a computer scientist.

But it is not the main reason. The main reason is that I want to know.

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\(^5\)and probably well over – the true maximum speed is classified.