# Summary

Algorithms are the step-by-step instructions used in computing for achieving desired results, much like recipes in cooking. In both cases the recipe designer has a certain controlled environment in mind for realizing the recipe, and foresees how the desired outcome will be achieved. The algorithms I discuss in this book are special. Unlike most algorithms, they can be run in environments unknown to the designer, and they learn by interacting with the environment how to act effectively in it. After sufficient interaction they will have expertise not provided by the designer, but extracted from the environment. I call these algorithms ecorithms. The model of learning they follow, known as the probably approximately correct model, provides a quantitative frame- work in which designers can evaluate the expertise achieved and the cost of achieving it.

算法是用于计算为实现预期的结果，就像在烹饪食谱的分步指导。在两种情况下配方设计-呃某些受控的环境，实现食谱，并预见到将如何实现所期望的结果。我在这本书中讨论的算法都是特别的。与大多数算法不同的是他们可以在运行环境未知设计师，和他们学习如何采取有效行动，在它与环境环境交互。经过充分的互动就有不提供的设计器，但从环境中提取出来的专门知识。我打电话给这些算法 ecorithms。学习他们遵循，称为可能大体正确的模型，该模型提供定量的框架工作的设计师可以评估取得的专门知识和实现它的成本。

These ecorithms are not merely a feature of computers. I argue in this book that such learning mechanisms impose and determine the character of life on Earth. The course of evolution is shaped entirely by organisms interacting with and adapting to their environments. This biological inheritance, as well as further learning from the environment after conception and birth, have a determining influence on the course of an individual’s life. The focus here will be the unified study of the mechanisms of evolution, learning, and intelligence using the methods of computer science.

这些 ecorithms 并不只是计算机的一项功能。我认为在这本书中，这种学习机制施加，确定地球上的生命的字符。进化过程中的是完全由有机体与除代理和适应其环境塑造的。此生物的继承，以及进一步从环境中学习怀孕后，有决定性影响的个人的生命历程。这里的重点将是统一的研究机制的演变、 学习和使用计算机科学的方法的情报。

The book has the following simple structure. Chapters 1, 2, and 4 set the scene for the natural phenomena to which the quantitative computational approach is to be applied. Chapter 3 is an introduction to computer science, particularly the quantitative study of algorithms and their complexity, and describes the background for the methodology used. Chapters 5, 6, and 7 contain the resulting theory for learning, evolution, and intelligence, respectively. The final chapters make some informal and more speculative suggestions with regard to some consequences for humans and machines.

这本书有以下的简单结构。1、 2 和 4 的章节设置现场为定量的计算方法将被应用到的自然现象。3 章是导论计算机科学，特别是算法的定量研究和它们的复杂性，并介绍了使用的方法的背景。5、 6 和 7 的章节分别包含为学习、 进化和情报，由此产生的理论。最后几章对人和机器使谈一些后果的一些非正式和更多的投机的建议。

# Chapter One Ecorithms

In 1947 John von Neumann, the famously gifted mathematician, was key- note speaker at the first annual meeting of the Association for Computing Machinery. In his address he said that future computers would get along with just a dozen instruction types, a number known to be adequate for ex- pressing all of mathematics. He went on to say that one need not be surprised at this small number, since 1,000 words were known to be adequate for most situations in real life, and mathematics was only a small part of life, and a very simple part at that. The audience reacted with hilarity. This provoked von Neumann to respond: “If people do not believe that mathematics is simple, it is only because they do not realize how complicated life is.”1

1947 年约翰 · 冯 · 诺依曼，著名数学家，是主讲人的计算机械协会第一次年度会议。在讲话中他说: 未来的计算机会相处十几只是指令类型，数已知的对前压所有的数学都是足够的。他接着说，一个不需要 sur-撬在这个小的数字，因为已知 1000 字要足够应对大多数情况下，现实生活中，和数学是只有一小部分的生活和一个非常简单的零件，在那。观众反应与欢乐。这 provoked · 冯 · 诺依曼作出回应:"如果人们不相信，数学是简单，它是只是因为他们不知道如何复杂的生活是"。1

Though counterintuitive, von Neumann’s quip contains an obvious truth. Einstein’s theory of general relativity is simple in the sense that one can write the essential content on one line as a single equation. Understanding its meaning, derivation, and consequences requires more extensive study and effort. However, this formal simplicity is striking and powerful. The power comes from the implied generality, that knowledge of one equation alone will allow one to make accurate predictions about a host of situations not even conceived when the equation was first written down.

虽然有悖常理，冯 · 诺依曼的妙语包含一个显而易见的事实。爱因斯坦的广义相对论理论是简单意义上，一个能在同一行中作为一个单一的方程写的基本内容。了解其含义、 派生和后果需要更广泛的研究和努力。然而，这种正式的简单性是引人注目和强大。力量来自于隐含的一般性原则下，单独的一个方程的知识会允许自己作出准确的预测很多的情况下甚至没有设想时，方程第一次写下来。

Most aspects of life are not so simple. If you want to succeed in a job inter- view, or in making an investment, or in choosing a life partner, you can be quite sure that there is no equation that will guarantee you success. In these endeavors it will not be possible to limit the pieces of knowledge that might be relevant to any one definable source. And even if you had all the relevant knowledge, there may be no surefire way of combining it to yield the best decision.

生活的大多数方面并不那么简单。如果你想要成功的工作除-在视图中，或在作出投资，或在选择人生伴侣，你可以肯定是不能保证你成功的方程。在这些工作中它将不可能限制可能与任何一个可定义源有关的知识的碎片。而且即使你有所有的相关的知识，可能没有万全之策相结合产生的最好的决定。

“This book is predicated on taking this distinction seriously. Those aspects of knowledge for which there is a good predictive theory, typically a mathematical or scientific one, will be called theoryful. The rest will be called theoryless. I use the term theory here in the same sense as it is used in science, to denote a “good, effective, and useful theory” rather than the negative sense of “only a theory.” Predicting the orbit of a planet based on Newton’s laws is theoryful, since the predictor uses an explicit model that can accurately predict everything about orbits. A card player is equally theoryful in predicting an opponent’s hand, if this is done using a principled calculation of probabilities, as is a chemist who uses the principles of chemistry to predict the outcome of mixing two chemicals.

"这本书被取决于认真对待这种区分。这些方面的知识是一个好的预测理论，通常数学或科学的人，将被称为 theoryful。其余将被称为 theoryless。我使用期限理论在这里在同一意义上，它用在科学中，来表示"好的、 有效的和有用的理论"而不是负面意义的"只是理论"。预测基于牛顿定律的轨道是行星的 theoryful，因为预测使用显式的模型，可以准确地预测轨道的一切。打牌的人是同样 theoryful 在预测对手的手里，如果这样做是使用原则计算的概率，一名化学家使用化学原理来预测混合两种化学物质的结果。

In contrast, the vast majority of human behaviors look theoryless. Nevertheless, these behaviors are often highly effective. These abundant theoryless but effective behaviors still lack a scientific account, and it is these that this book addresses.

与此相反的是，绝大多数的人类行为看 theoryless。然而，这些行为往往是非常有效的。这些丰富的 theoryless 但有效行为仍然缺乏科学的解释，和它是这本书涉及的这些。

“The notions of the theoryful and the theoryless as used here are relative, relative to the knowledge of the decision maker in question. While gravity and mechanics may be theoryful to a physicist, they will not be to a fish or a bird, which still have to cope with the physical world, but do so, we presume, without following a theory. Worms can burrow through the ground without apparently any understanding of the physical laws to which they are subject. Most humans manage their finances adequately in an economic world they don’t fully understand. They can often muddle through even at times when experts stumble. Humans can also competently navigate social situations that are quite complex, without being able to articulate how.

"Theoryful 和 theoryless 用在这里的概念是相对的相对于决策者问题的知识。虽然重力和力学可能 theoryful 一位物理学家，他们不会对一条鱼或者一只鸟，当中仍有应付物理的世界，但这样做，我们相信，没有按照理论。蠕虫可以挖洞通过地面没有显然任何他们受到的物理法则的理解。大多数人类管理他们充分参与经济的世界，他们不完全理解的财务状况。他们往往能蒙混过关，有时甚至当专家跌倒。人类也胜任可以导航是相当复杂，不能表达的社会情况如何。

“In each of these examples the entity manages to cope somehow, without having the tenets of a theory or a scientific law to follow. Almost any biological or human behavior may be viewed as some such coping. Many instances of effective coping have aspects both of the mundane and also of the grand and mysterious. In each case the behavior is highly effective, yet if we try to spell out exactly how the behavior operates, or why it is successful, we are often stumped. How can such behavior be effective in a world that is too complex to offer a clear scientific theory to be followed as a guide? Even more puzzling, how can a capability for such effective coping be acquired in the first place?”

"在每个示例实体管理应付不知怎的没有一个理论或科学的规律，遵循的原则。几乎任何生物或人类的行为可能被视为一些这种应对。很多情况下的有效应对有世俗的和宏伟和神秘的方面。在每个案件的行为是高度有效，但如果我们尝试拼出确切的行为是如何运作的或者为什么它是成功的我们是经常难住了。如何这样的行为能有效在是太复杂，无法提供明确的科学理论作为指导应遵循的世界呢?更令人费解的怎么可以这样有效的应对能力获得放在第一位?"

Science books generally restrict their subject matter to the theoryful. However, I am impressed with how effectively life forms “cope” with the theoryless in this complex world. Surely these many forms of coping have some commonality. Perhaps behind them all is a single basic phenomenon that is itself subject to scientific laws.

科学书籍一般限制其主题 theoryful。然而，我是如何有效地生命形式"应付"与 theoryless 在这个复杂的世界的印象。当然这些许多形式的应对有一些共性。也许在他们后面都是一个单一的基本现象，本身就是科学的法律。

This book is based on two central tenets. The first is that the coping mechanisms with which life abounds are all the result of learning from the environment. The second is that this learning is done by concrete mechanisms that can be understood by the methods of computer science.

这本书基于两个核心原则。第一是应对机制生活丰富都是从环境环境学习的结果。第二是这种学习通过具体的机制，可以理解的计算机科学的方法。

On the surface, any connection between coping and computation may seem jarring. Computers have traditionally been most effective when they follow a predictive science, such as the physics of fluid flow. However, computers also have their softer side. Contrary to common perception, computer science has always been more about humans than about machines. The many things that computers can do, such as search the Web, correct our spelling, solve mathematical equations, play chess, or translate from one language to another, all emulate capabilities that humans possess and have some interest in exercising. Depending on the task, the performance of present-day computers will be better or worse than humans. But in regarding computers merely as our slaves for getting things done, we may be missing the point. The overlap between what computers and humans do every day is already vast and diverse. Even without any extrapolation into the future, we have to ask what computers already teach us about ourselves.

表面上看，任何应对和计算之间的连接可能显得刺耳。当他们按照预测的科学，如流体流动的物理计算机历来最有效。然而，com 电脑也有自己温柔的一面。与普遍看法相反计算机科学一直是关于有关机器比人类更多。很多事情，计算机可以做，如搜索 Web，纠正我们的拼写、 解决数学方程、 下棋，或从一种语言翻译到另一个，所有模拟功能人类拥有和行使的一些兴趣。根据任务，当今的计算机的性能将比人类好或差。但方面 ing 在计算机中只是作为我们做事的奴隶，我们可能想着点。每天做什么计算机和人类之间的重叠部分已经是庞大和多元化。即使没有任何外推到福真的，我们要问计算机已经教给我们什么......

The variety of applications of computation to domains of human interest is a totally unexpected discovery of the last century. There is no trace of any- one a hundred years ago having anticipated it. It is a truly awesome phenomenon. Each of us can identify our own different way of being impacted by the range of applications that computers now offer. A few years ago I was interested in the capabilities of a certain model of the brain. In a short, hermit-like span of a few weeks I ran a simulation of this model on my laptop and wrote up a paper based on the calculations performed by my laptop. I used a word processor on the same laptop to write and edit the article. I then emailed it off to a journal again from that laptop. This may sound unremarkable to the present-day reader, but a few generations ago, who would have thought that one device could perform such a variety of tasks? Indeed, while for most ideas some long and complex history can be traced, the modern notion of computation emerged remarkably suddenly, and in a most complete form, in a single paper published by Alan Turing in 1936.2

各种应用程序域对人类感兴趣的是计算的上个世纪完全意外的发现。一百多年前有预期它还有没有跟踪任何人。它是真正可怕现象。我们每个人都可以确定我们自己不同的方式受到计算机现在提供的应用范围。几年前我很感兴趣，大脑某些模型的功能。在短短的几个星期隐士般的短我跑这个模型模拟在我的笔记本上，写了一份文件，基于我电脑上执行的计算。我用于文字处理器相同的笔记本电脑上编写和编辑艺术单粒子轨迹。我然后通过电子邮件发送它掉到某一日志再次从那台手提电脑。这可能听起来不起眼到现代的读者，但几代之前，都没有想到，一个设备可以执行各种各样的任务吗?事实上，虽然大多数的想法可以追溯一些漫长而复杂的历史，现代概念的计算出现了非常突然，和以最完整的形式，在一张纸在 1936.2 发表的 Alan Turing

Science prior to that time made no mention of abstract machines. Turing’s theory did. He defined the mathematical notion of computation that our all- pervasive information technology now follows. But in offering his work, he made it clear that his goal went beyond understanding only machines: “We may compare a man in the process of computing a real number to a machine which is only capable of a finite number of conditions.” With these words he was declaring that he was aiming to formalize the process of computation where a human mechanically follows some rules. He was seeking to capture the limits of what could be regarded as mechanical intellectual work, where no appeal to other capabilities such as intuition or creativity was being made.

之前这段时间的科学抽象机器没有提到。图灵的理论做了。他定义我们所有普遍存在的信息技术现在跟随的计算的数学概念。但在提供他的工作，他清楚，他的目标超出了理解只有机器:"我们可能比较过程中计算一个实数的一台机器，是唯一能够条件有限数目的人"。说完这些话他宣布，他的目标正式确定在哪里人机械地遵循一些规则的计算过程。他想要捕捉的什么可以被视为机械的智力劳动，有人被其他功能，如直觉或创造力没有呼吁限制。

Turing succeeded so well that the word computation is now used in exactly the sense in which he defined it. We forget that a “computer” in the 1930s referred to a human being who made a living doing routine calculations. Speculations that philosophers or psychologists entertained in earlier times as to the nature of mechanical mental capabilities equally dim in the memory. Turing had discovered a precise and fundamental law that both living and inert things must obey, but which only humans had been observed to exhibit up to that time. His notion is now being realized in billions of pieces of technology that have transformed our lives. But if we are blinded by this technological success, we may miss the more important point that Turing’s concept may enable us to understand human activity itself.

图灵成功所以那词计算是现在用在前-明目张胆地在其中他定义它的含义。我们忘了在 20 世纪 30 年代的"计算机"指作做例行规律性生活的人。哲学家或心理学家受理在更加早期的时期的机械的心理功能性质的猜想同样暗淡在内存中。图灵发现了精确和基本的法律，丽芙 ing 和惰性物质必须服从，但其中唯一的人类已经被观察到陈列到那个时候。他的想法，现在在数以十亿计的技术，改变了我们的生活。但如果我们蒙蔽了此技术的成功，我们可能会错过，图灵的概念可能会使我们能够理解人类活动本身更重要的一点。

This may seem paradoxical. Humans clearly existed before Turing, but Turing’s notion of computation was not noticed before his time. So how can his theory be so fundamental to humans if little trace of it had even been suspected before?

这看起来似乎自相矛盾。人类显然存在之前图灵机，但计算图灵机的概念不注意到之前，他的时间。所以他的理论如果怎能如此基本的人类小的微量甚至曾怀疑之前吗?

My answer to this is that even in the pre-Turing era, in fact since the be- ginning of life, the dominating force on Earth within all its life forms was computation. But the computations were of a very special kind. These computations were weak in almost every respect when compared with the capabilities of our laptops. They were exceedingly good, however, at one enterprise: adaptation. These are the computations that I call ecorithms—algorithms that derive their power by learning from whatever environment they inhabit, so as to be able to behave effectively in it. To understand these we need to understand computations in the Turing sense. But we also need to refine his definitions to capture the more particular phenomena of learning, adaptation, and evolution.

我的答案是，即使在前图灵时代，事实上因为是: 轧花的生活，在地球上一切生命形式内的主导力量是计算。但计算是一种非常特殊。这些楼板很弱在几乎每一个方面与我们的笔记本电脑社会荫庇相比。他们都非常的好，但是，在一个输入企业: 适应。这些都是我叫 ecorithms 的计算 — — al gorithms 派生通过学习无论环境如何从他们居住，以便能够在它有效地表现他们的力量。要了解这些我们需要了解在图灵意义上的计算。但我们还需要改进他的定义，以捕获的学习、 适应和进化的更特殊的现象。

Understanding learning has been one of my personal research goals for several decades. The natural phenomenon of young children learning is extraordinary. A spectacular facet of this learning is that, beyond remembering individual experiences, children will also generalize from those experiences, and very quickly. After seeing a few examples of apples or chairs, they know how to categorize new examples. Different children see different examples, yet their notions become similar. When asked to categorize examples they have not seen before, their rate of agreement will be remarkably high, at least within any one culture. Young children can sort apples from balls even when both are round and red.

了解学习一直是我个人的研究目标了几十年。幼儿学习的自然现象是怪。这种学习的壮观一面是超越记忆的个人经验，孩子将也概括从这些经验，并很快。在看到苹果或椅子的几个例子，他们知道如何进行分类的新例子。不同的孩子看到不同的例子，但他们的想法变得相似。当要求分类他们以前没见过的例子，他们的协议率会非常高，至少内任何一种文化。年幼的孩子可以排序从球甚至苹果都是圆的红色的时候。

This ability to generalize looks miraculous. Of course, it cannot really be a miracle. It is a highly reproducible natural phenomenon. Ripe apples fall from the tree to the ground predictably enough that one can base a universal law of gravitation on this phenomenon. Children generalizing successfully from their specific experiences manifest a similarly predictable phenomenon, which therefore also begs for a scientific explanation. I seek to explain this in terms of concrete computational processes.

这种能力来概括看起来很神奇。当然，它不能真的是个奇迹。它是一个高度重复性的自然现象。熟透了的苹果落从树上到地面不出所料，一个人可以依据对这一现象万有引力定律。孩子们从他们具体的经验成功地推广表现同样可预测的现象，因此也乞求一个科学的解释。我试图解释这具体的计算过程。

The phenomenon of generalization has been widely discussed by philosophers for millennia. It has been called the problem of induction. I have found that as a scientist I have some advantages over philosophers: It is suf- ficient to aim to capture the fundamental part of a specific reproducible phenomenon. I need not explain all of the many senses in which the words induction or generalization have been used. Scientific discovery—for example, Johannes Kepler discovering his laws of planetary orbits—may have some commonality with the phenomenon of generalization exhibited by children learning words, but it may be a secondary and harder to reproduce by- product of a more basic and fundamental capability. Turing did not attempt to capture all the connotations that the word computing may have had in his day. He sought only to uncover a phenomenon associated with that word that had fundamental reality independent of any word usage.

千百年来，斐洛 sophers 被广泛讨论的泛化现象。它被称为归纳问题。我发现作为一名科学家，我有一些哲学家的优势: 它是主要旨在捕获特定重现现象的基本部分。我不需要解释所有在其中的很多感官尚未使用词在生产或泛化。科学发现 — — 例如，约翰内斯 · 开普勒发现他的行星轨道定律 — — 可能有一些共性与泛化现象所表现的儿童学习单词，但它可能产生的次要的和难以重现的更基本和基本能力的产品。图灵亦未能捕获 word 计算可能已经在他的一天的所有内涵。他只是试图揭开与有独立于任何词的用法的基本现实这个词相关联的现象。

What kind of explanation of induction do we need? Does it need to be mathematical? There is no better answer to this than what is implicit in the work of Turing himself. I have already referred to his successful mathematic- al formulation of computation. But he is also famous for the notion that is now known as the Turing Test, which he offered as a test for recognizing whether a machine can be considered to think. A simplified definition is as follows. A machine passes the Turing Test if a person, conversing with it via remote electronic interactions, cannot distinguish it from a person. The Turing Test is an important notion, and researchers in artificial intelligence have not succeeded in either building machines that can pass the test or in showing it to be irrelevant. However, it is an informal notion. Unlike Turing’s mathematical definition of computation, it does not tell us how exactly to proceed in order to emulate thinking. As a result, it has not led to progress in artificial intelligence remotely comparable to the success of general computation.

我们需要什么样的感应解释?它不必是数学?还有没有更好的答案，这比什么是隐式的图灵自己工作。我已经提到他成功的数学基地制定的计算。但他也是著名的现在被称为图灵测试，他主动提出作为识别是否可以被视为一台机器，想测试的概念。一个简化的定义是，如下所示。如果一个人，与它交谈，通过远程电子相互作用，不能区分它从一个人一台机器通过图灵测试。Tur ing 测试是一个重要的概念，并在人工智能领域中的研究者不成功可以通过考试或建筑机器或显示它是不相关。然而，它是一个非正式的概念。与 Tur ing 计算的数学定义，不同的是它并没有告诉我们到底是如何来行事，以模仿思维。结果，它并未在人工智能远程媲美成功的一般计算方面取得进展。

Hence the right goal must be to find a mathematical definition of learning of a nature similar to Turing’s notion of computation, rather than an informal notion like the Turing Test. After all, where would we be if Turing had given for computation only an informal definition? Let us think about that. What would have been an informal notion of the “mechanically computable” that would have sounded plausible in Turing’s time? How about this: “A task is mechanically computable if and only if it can be computed by a person of average intelligence while at the same time doing a mundane but exacting task, such as eating spaghetti.” Few could have disputed the reasonableness of such a definition. But I doubt such a definition in 1936 could have spawned the twenty-first century we see around us.

因此正确的目标一定要找到学习性质的数学定义类似于计算，图灵机的概念，而不是一个非正式的概念，像图灵测试。毕竟，在那里我们会如果图灵曾给出了计算只是一个非正式的定义呢?让我们想想的。什么会被一个非正式的"机械 com-putable"的概念，会有听起来似乎可信在图灵的时间吗?这个怎么样:"的任务是机械可计算当且仅当它可以计算一个人的平均智力同时做一个平凡但也很严格的任务，如吃意大利面条。很少有人能争执原因手术的这一定义。但我怀疑这种定义在 1936 年可能繁衍了第二十一世纪我们看到在我们周围。

At the heart of my thesis here is a mathematical definition of learning. It is called the PAC or the probably approximately correct model of learning, and its main features are the following:3 The learning process is carried out by a concrete computation that takes a limited number of steps. Organisms can- not spend so long computing that they have no time for anything else or die before they finish. Also, the computation requires only a similarly limited number of interactions with the world during learning. Learning should en- able organisms to categorize new information with at most a small error rate. Also, the definition has to acknowledge that induction is not logically fail-safe: If the world suddenly changes, then one should not expect or re- quire good generalization into the future.

在我的心在这里是论文的学习数学定义。它被称为 PAC 或学习，可能大约正确模型，其主要特点是学习的过程由具体的计算采用有限的数量的步骤如下: 3。生物体不能花这么长时间计算，他们都没有时间做别的事情死之前他们完成。此外，计算在学习过程中需要只有同样有限的数目与世界的互动。学习应该 en-能生物进行分类的新信息与最小错误率。定义而且，不得不承认感应并不是逻辑上万全之策: 如果世界突然发生变化，则不应指望或成未来再需要良好的泛化。

The biology of living organisms can be described in terms of complex circuits or networks that act within and between cells. Our biology is based on proteins and the interactions among them. Our DNA contains more than 20,000 genes that describe various proteins. Additionally, the DNA encodes descriptions of the regulation mechanism, a specification of how much new protein of each kind is to be produced, or expressed. This overall regulation mechanism is absolutely fundamental to our biology, and is called the protein expression network. It is of enormous complexity. Even though many of its details remain to be discovered, we can ask: How have these well-functioning, highly intricate networks with so many interlocking parts come in- to being? I believe that all these circuits are the result of some learning process instigated by the interactions between a biological entity and its environment.

生物体的生物可以描述复杂的 cir cuits 或行动内及细胞间的网络。我们的生物学基于蛋白质和它们之间的交互。我们的 DNA 包含超过 20000 个描述各种各样的蛋白质的基因。此外，DNA 编码的调控机制的描述，多少新的蛋白质，每种规格是被生产，或者表示。这个整体的规管机制是我们生物的根本原则，被称为 pro 蛋白表达网络。它是极其复杂。尽管很多它的细节问题仍被发现，我们可以问: 怎么有这么多的联锁部分这些调节功能好，高度复杂网络来到在-被?我相信所有这些电路是由一个生物实体与它的环境之间的相互作用煽动一些学习过程的结果。

Life’s interactions can be viewed in terms of either a single organism’s life- time or the longer spans during which genes and species evolve. In either case the information gained by the entity from the interaction is processed in some mechanical way by what I call an ecorithm. The primary purpose of the ecorithm is to change the circuits so that they will behave better in the environment in the future and produce a better outcome for the owner.

生活中的相互作用可以看作一个单一的有机体生命时间或其间基因和物种进化的更长的时间跨度。在任一情况下一些机械的方式称之为 ecorithm 处理由实体的交互作用中获得的信息。Ecorithm 的主要目的是要改变电路，将在未来环境环境中更好地表现为所有者产生更好的结果。

Human biochemistry is an important enough topic. However, our neural circuits, comprising some tens of billions of neurons, may be viewed as being involved in our personal experiences even more intimately. Our psychological behavior is controlled by these circuits. How do these circuits arise in evolution, and how are they updated during life? By the same arguments they too must be the result of information obtained from interactions, by ourselves or our ancestors, and incorporated in our genes or brain by some adaptive mechanism.

人类生化是足够重要的课题。然而，我们的神经回路，包括一些数以亿计的神经元，可视为更密切参与我们个人的经验。我们心理基地的行为被受这些电路。如何做这些电路出现在进化中，而他们如何在生活过程中更新呢?相同的参数由他们也必须信息相互作用，通过我们自己或我们的祖先，并列入我们的基因或大脑由一些自适应机制的结果。

If biological circuits are fundamentally shaped by learning processes, there seems little chance of understanding them, or their manifestations in our psychology, unless we recognize their origins in learning. We may not yet know in detail the actual ecorithms used in biology on Earth. However, the fact that our behaviors have their origins in such learning algorithms already has implications.

如果生物电路从根本上由学习过程，那里似乎理解他们，或对我们的心理，他们表现的机会不大，除非我们认识到他们的起源在学习。我们可能还不知道详细实际的 ecorithms 用在地球上的生物。然而，我们的行为已经有这种学习算法中的他们的起源，也有含义。

Earlier I listed as two central tenets that the behaviors that need explanation all arose from learning, and that this learning can be understood as a computational process. These tenets are not offered here as mere unproved assumptions, but as the consequences of the assumption that life has a mechanistic explanation.

较早前的行为，需要解释理由都源于学习，和这种学习可以被理解为一个计算过程列出作为两个中心原则。这些信条提供不在这里，仅仅是未经证实的假设，而是假定生命有一种机械论的解释的后果。

The argument that these tenets actually follow from the formulation of ecorithms goes as follows: I start with the mechanistic assumption that bio- logical forms came into existence as a result of concrete mechanisms operating in some environments. These mechanisms have been of two kinds, those that operate in individuals interacting with their environment, and those that operate via genetic changes over many generations. I then make two observations. First, ecorithms are defined broadly enough that they encompass any mechanistic process. This follows from the work of Turing and his con- temporaries that established the principle, known as the Church-Turing Hypothesis, that all processes that can be regarded as mechanistic can be captured by a single notion of computation or algorithm. Second, ecorithms are also construed broadly enough to encompass any process of interaction with an environment. From these two observations one can conclude that the coping mechanisms of nature have no sources of influence on them that are not fully accounted for by ecorithms, simply because we have defined ecorithms broadly enough to account for all such influences.

这些信条实际上遵循从 ecorithms 制定的论点如下: 我从开始就机械论的假设这种生物 — — 逻辑的形式进入了由于具体的机制经营 ing 在某些环境中的存在。这些机制已经的两种，在个人与他们的环境进行交互操作的那些和那些在许多世代经营通过遗传变化。我然后让两个 ob 断面。首先，ecorithms 的定义很广泛足够他们包括任何机械的过程。这源于图灵和确立了原则，称为丘奇-图灵 Hy-数，可以视为一样机械的所有进程都可以盖水气由一个单一的概念，计算或算法的他 con-临时人员的工作。第二，ecorithms 是也解释得条件宽泛足以为包括任何与环境相互作用的过程。从这两点就可以总结出自然的应对机制有没有来源对他们的影响，不充分所占 ecorithms，只是因为我们有定义生态思想足够宽广占所有这类影响。

To put this in a different way, the news reported here is that there is a burgeoning science of learning algorithms. Once the existence of such a science is accepted, its centrality to the study of life is more or less self-evident.

要把这放在以不同的方式，报道这里是 bur geoning 科学的学习算法。一旦接受了这种科学的存在，其至关重要的学习生活是更多或更少不言而喻的。

Of course, the reader should be cautious when confronted with purported logical arguments such as the one I just gave. Indeed, later chapters will ad- dress the general pitfalls of reasoning about theoryless subject matter. It is appropriate, therefore, to attempt to corroborate my proposition. Is there somewhere we can turn for a sanity check? The answer is machine learning, a method for finding patterns in data that are usefully predictive of future events but which do not necessarily provide an explanatory theory.

当然，读者应谨慎面对所谓逻辑参数如那个我只是给了时。的确，后面的章节将 ad-衣服 theoryless 主题推理一般缺陷。因此，适当的是企图证实我的主张。有什么地方我们可以找一个检查吗?答案是机器学习、 数据有效地预测未来事件的但这不一定提供的解释性理论中寻找模式的一种方法。

Machine learning is already a widely used technology with diverse applications. For example, companies such as Amazon and Netflix make recommendations to shoppers based on the predictions of learning algorithms trained on past data. Of course, there is no theory of which books or movies you will like. You may even completely change your tastes at any time. Nevertheless, using machine learning algorithms, it is possible to do a useful job in making such recommendations. Financial institutions likewise use machine learning algorithms, in their case, for example, for detecting whether individual credit card purchase attempts are likely to be fraudulent. These algorithms pick up various kinds of relevant information, such as the geo- graphical pattern of your previous purchases, to make some decisions based on data collected from many past transactions. The development of the learning algorithms used may well be theoryful. But this again does not mean that fraud itself is theoryful. New kinds of fraud are being invented all the time. The algorithms merely find patterns in past credit card purchases that are useful enough to give financial institutions a statistical edge in coping with this area of the theoryless.

机器学习是已经广泛使用的技术与多样应用规格。例如，亚马逊和 Netflix 等公司对购物者基于预测的学习算法训练以过去的数据进行征询。当然，是没有理论的哪些书或电影，你会喜欢。甚至完全可以在任何时候改变你的口味。然而，使用机器学习算法，它是可能做到在作出有关建议是有用的工作。金融机构同样使用机器学习算法，在他们的情况，例如，为检测轮训-呃个别信用卡购买尝试是可能存在欺诈行为。这些算法接各种相关的信息，如您以前的购买，地理图形模式作出一些决定基于数据收集从过去交易的很多。所使用的学习算法的发展可能是 theoryful。但这又并不意味着欺诈行为本身是 theoryful。新类型的欺诈被发明出来的时间。算法只是找到模式在过去有助于给金融机构统计的边缘在缔约方会议-ing 与这一领域的 theoryless 的信用卡购物。

Much of everyday human decision making appears to be of a similar nature—it is based on a competent ability to predict from past observations without any good articulation of how the prediction is made or any claim of fundamental understanding of the phenomenon in question. The predictions need not be perfect or the best possible. They need merely to be useful enough. The fact that these algorithms are already in widespread use, and produce useful results in areas most would regard as theoryless, is good evidence that we are on the right track.

很多人在日常决策似乎类似性质的 — — 它基于胜任能力预测从过去的观察，没有任何清晰的预测怎样制成或任何索赔的基本理解的现象。预测不需要完美的或最好的可能。他们仅仅需要足够有用。这些算法已被广泛使用，并产生有益的结果，地区大部分会视为 theoryless，其实好的证据表明，我们是在正确的轨道。

However, the idea of an ecorithm goes well beyond the idea of machine learning in its current, general usage. Within the study of ecorithms several additional notions beyond the learning algorithms themselves are included. First, there is the notion that it is important to specify what we expect a learning algorithm to be able to do before we can declare it to be successful. Second, using such a specification, we can then discuss problems that are not learnable—some environments will be so complex that it is impossible for any entity to cope. Third, there is the question of how broad a functional- ity one wants to have beyond generalization in the machine learning sense. To have intelligent behavior, for example, one needs at least a reasoning cap- ability on top of learning. Finally, biological evolution must fit somehow into the study of coping mechanisms, but it is not clear exactly how, since traditional views of evolution do not exactly fit the machine learning paradigm. In studying ecorithms, we want to embrace all of these issues, and more.

然而，ecorithm 的想法远远的机器学习方法在其当前的、 一般的用法的想法。内研究几个额外概念超越自己的学习算法是 ecorithms 的包括的。首先，是很重要的是要指定我们所期望的一种学习算法能够做之前，我们可以将其声明为成功的概念。第二，使用这种规范，然后，我们可以讨论并不是可以学习的问题 — — 一些环境将是如此复杂，它是无法应付的任何实体。第三，是如何广泛功能-ity 一个想要超越在机器学习意识的泛化的问题。例如，有智能的行为，你需要至少推理能力在学习上。最后，生物进化必须以某种方式融入应对机制的研究，但尚不清楚到底如何了，因为演化的传统观点并不完全适合机器学习的范例。在研究 ecorithms，我们想要拥抱所有的这些问题，和更多。

The problem of dealing with the theoryless is ever present in our lives. Every day we are forced to put our trust in the judgment of experts who operate outside the bounds of any strict science. Your doctor and car mechanic are paid to make judgments, based on their own experience and that of their teachers. We presume that their expertise is the result of learning from a substantial amount of real-world experience and, for that reason, is effective in coping with this complex world. Their expertise can be evaluated by how well their diagnoses and predictions work out. In some areas we can evaluate performance, at least after the fact.

Theoryless 处理的问题是在我们的生活中一直存在的。每一天，我们不得不把我们信任的专家判断谁 op-仍超出任何严格的科学。您的医生和汽车机械师支付做出判断，基于自己的经验和他们的老师。我们推测他们的专业知识是从大量的现实世界的经验中学习的结果，并为此原因，是有效地应对这个复杂的世界。如何预测及其诊断奏效，可以评价他们的专业知识。在一些地区我们可以评价性能，至少后这一事实。

We are also exposed every day to commentators and pundits whose diagnoses and predictions are infrequently checked for ultimate accuracy. We hear about what will happen in politics, the stock market, or the economy, but these predictions often seem hardly better than random guessing.

我们也受到评论家和学者们经常检查其直径 gnoses 和预测最终精度每日。我们听到将会发生什么政治，股票市场或经济体系，但这些预言经常看起来几乎不比随机猜测。

In late 2008 Queen Elizabeth II asked a group of academics why the world financial crisis had not been predicted. She was not the only one asking this question. Was the crisis inherently unpredictable in some sense, or was the failure due to some gross negligence? After the crisis a substantial amount of public discussion pertained to this question. Is there a rational way of predicting rare events? Why do humans have so many intellectual frailties and behave as irrationally as they do? Why are humans subject so easily to deception and self-deception? Why do humans systematically delude them- selves into thinking that they are good predictors of future events even if they are not?

在 2008 年年底英国女王伊丽莎白二世问一群学者为什么世界金融危机没有预测。她不是唯一问这个问题。是这场危机在某种意义上，固有的不可预知或失败是由于一些重大的过失吗?在危机后大量的公共讨论涉及到这个问题。有理性的方法估测的罕见的事件吗?人类为什么有这么多的智力弱点和作为他们一样不理性的行为?为什么人类如此轻易服从德贯穿和自欺欺人?为什么做人类系统地诱使他们自我觉得他们是很好地预测未来的事件，即使他们不是?

Many reasons have been given for the difficulty of making predictions, and the mistakes that people are prone to make have been widely analyzed.4 The following, for example, is an instructive argument. After any significant historical event numerous explanations of the causes are offered. These explanations can be so beguilingly plausible that we easily mistake them for actual causes that might have been detected before the events in question. We are then communally led into the belief that world events have identifiable causes and are generally predictable. Hence popular disappointment that the world financial crisis had not been better anticipated can be ascribed to widespread over expectation and naïveté with regard to the possibility of making predictions.

很多的理由，做出预测，难度和人都容易犯的错误已经广泛护坡以下示例中，是有教育意义的参数。任何重大的历史事件之后许多的原因的解释有。这些解释可以如此诱人振振有词，我们很容易会误以为他们的实际原因，可能在有关事件发生之前发现。我们是然后集体领进信仰的世界的事件有可识别的原因是一般可预见的。因此世界金融危机没有更好地预料的流行失望可以归因于普遍期望和天真就作出预测的可能性。

This book departs from this approach and takes an opposing, more positive view. While making predictions may be inherently difficult, and we humans have our special failings, human predictive abilities are substantial and reason enough for some celebration. Humans, and biological systems generally, do have an impressive capability to make predictions. The ability of living organisms to survive each day in this dangerous world is surely evidence of an ability to predict the consequences of their actions and those of others, and to be prepared for whatever happens, and be rarely taken totally by surprise. In human terms, the fact that we can go through a typical day, one that may include many events and interactions with others, and be seldom surprised is testament surely of our good predictive talents. Of course, the domains in which we make these reliable predictions often relate only to everyday life—what other people will say or other drivers do. They are mundane, almost by definition. But even mundane predictions become mystifying once one tries to understand the process by which the predictions are being made, or tries to reproduce them in a computer.

这本书最大的背离这种做法又反对，更多的假定我认为。预测可能是内在的困难，而我们人类有特别缺点，人类的预测能力大，足够一些庆祝的理由。人类和生物系统一般，具有一种令人印象深刻的能力以做出预测。生物体的能力，在这个危险的世界中生存的每一天肯定是能够预测自己行为的后果的证据，与其他人，并准备无论发生什么事，和很少完全意外的惊喜。在人类的条款，但事实上，我们可以通过典型的一天，可能包括许多事件和与他人的互动和很少会感到惊讶的那个肯定是证明我们良好的预测人才。当然，我们经常使这些可靠的预测的领域涉及只到日常生活 — — 其他人会说或其他驱动程序做。他们是世俗的几乎是顾名思义。但即使世俗预测变得神秘，一旦一个尝试理解的过程所预测正在作出，或试图重现他们在一台计算机。

From this viewpoint, the general disappointment that the world financial crisis had not been better predicted was not based entirely on naïve illusion. It was based on the well-justified high regard we have for our predictive abilities, and so it would be clearly to our advantage to identify why they failed. It may be that the world was changing in such a random fashion that the past did not even implicitly contain reliable information about the future. Or perhaps the past did indeed contain this information, but that it was some- how so complex that it was not practically feasible to dig it out. A third case is that prediction was indeed feasible, but the wrong algorithm or the wrong data had been used.

从这个角度来看，普遍感到失望，不更好地预测世界金融危机并非完全基于天真的幻想。它基于的理由充足的高度重视，我们对在我们预测的技能促，所以毫无疑问这将是对我们有利，要找出失败的原因。它可能是，世界在变化以随机的方式，过去并不甚至隐式包含关于未来的可靠信息。或也许过去确实包含此信息，但它是一些如何如此复杂，它不是实际可行，要把它挖出来。第三个案件是预测是确实可行的但曾经被错误的算法或错误的数据。

The study of ecorithms is concerned with delineating among these possibilities. Having the ability to make these distinctions among topics of every- day concern, such as predictions about the course of the economy, seems important. One may be able to do more than merely lament human frailties in this regard. Are there inherent reasons why reliable predictions are not possible regarding the course of a country’s economy? Perhaps one can show that there are. It would then follow that there is no reason to listen to pundits other than for entertainment.

Ecorithms 的研究与界定这些竞技荫庇之间有关。莱温斯基看起来有能力做这些区分等课程的经济预测每一天关注的主题之一。一个人也许能够做更多，而不仅仅是悲叹人性弱点在这方面。有其内在原因为什么可靠的预测不是乘载关于该国经济的课程吗?也许一个可以显示是有的。然后便是要倾听双关-资讯科技署署长以外的娱乐。

Computation allows one to construct concrete situations in which the world does reveal sufficient information for prediction in principle, but not in practice. Consider the area of encryption. If messages in the wireless connection of your home computer are encrypted, the intention is that if your neighbor listens in, he should not be able to get any information about what you are doing. Even if he listens in over a long period and does clever computations on the data he collects using a powerful computer, he should not be able to invade your privacy. This is another way of saying that the environment defined by your enciphered messages should be too complex for your neighbor, or anyone else, to make any sense of.

计算允许一个构造的世界确实暴露出足够的信息，预测原则，但不是在实践中的具体情况。考虑加密的区域。如果您的家庭计算机无线词库中的邮件加密的意图是如果你的邻居听，他不应该能够获取任何信息关于你在做什么。即使他很长一段听着，不聪明楼板上他收集使用功能强大的计算机的数据，他应该不能侵犯你的隐私。这是另一种说法由您加密的消息定义环境环境应该过于复杂，你的邻居，或者任何人，任何意义。

How can entities cope with what they do not fully understand? The simplest living organisms have had to face this problem from the beginnings of life. With limited mechanisms they had to survive in a complex world and to reproduce. Every evolving species has faced a similar problem, as do individual humans going through their daily lives. I shall argue that solutions to these problems have to be sought within the framework of learning algorithms, since this is the mechanism by which life extracts information from its environment. By the end of the book I hope to have persuaded the reader that when seeking to understand the fundamental character of life, learning algorithms are a good place to start.

实体如何应付他们不完全明白的?最简单的生物体都不得不面对这一问题从人生的起点。有限的机制与他们曾在一个复杂的世界中生存并繁殖。每个不断变化的物种已面临类似的问题，要通过他们的日常生活的个体的人一样。我会争辩说有学习 al-gorithms，因为这是生活中的信息提取从它的环境的机制的框架内寻求解决这些问题的办法。通过书的结尾我希望能够说服读者，当试图理解生活的基本特征，学习算法是一个很好的地方开始。

# Chapter Two Prediction and Adaptation

Only adapt.

ADAPTED FROM E. M. FORSTER

只有适应。 改编自 E.M.福斯特

“You never walk into a situation and believe that you know better than the natives. You have to listen and look around. Otherwise you can make some very serious mistakes.”1 This was a lesson that Kofi Annan, the former Secretary General of the United Nations learned, not on some far-flung diplomatic posting for the UN, but as a young man in St. Paul, Minnesota. He had arrived from Africa to study economics as an undergraduate. Inexperienced as he was with cold weather, when he first saw local students wearing ear muffs he thought they looked ridiculous. But after walking round the cam- pus on a cold day, he went out to buy some for himself.

"你永远不会走进一种情况，相信你知道比当地人更好。你必须听，看看周围。否则你会令一些非常严重的错误"。1 这是科菲 · 安南，前美国证券交易委员会-管理学联合国一般学，不是在一些偏远的外交-马蒂奇过帐为联合国，但作为一个年轻的人，在明尼苏达州的圣 Paul 一个教训。他来到从非洲学习经济学作为一名大学生。正如他与寒冷的天气，当他第一次看到戴耳罩他以为他们显得滑稽可笑的本地学生没经验的新手。但后走轮凸轮脓在一个寒冷的日子，他出去买一些给自己。

The logic of ecorithms has much in common with Annan’s analysis. That logic emphasizes listening and looking around. It encourages caution in applying specialized expertise gained in one environment to another, and gives respectful deference to observed experience. It says that it is we who must seek to adapt.

Ecorithms 的逻辑有许多共同之处安南的分析。这种逻辑强调听和四处张望。它鼓励谨慎在 ap-行走在一个环境到另一个，获得的专门的知识和尊重尊重给观察到的经验。它说，它是我们必须设法适应的人。

Such an adaptive imperative is absent from most aphorisms. “Neither a borrower nor a lender be” urges one to act in a specific way rather than to adapt to one’s environment. The pitfalls of following such non adaptive advice are clear. While the advice may be good in some circumstances, perhaps those from which it was derived, in others it may not be.

这种自适应的当务之急是缺席从大多数的警句。"借款人和贷款人都不是"敦促一以特定的方式行事，而不是去适应一个人的环境。遵循这种非广告副的陷阱是清楚的。虽然建议可能在某些情况下，也许那些它源自，好在他人不可能。

Annan’s strategy has the strength that it accepts that there are many possible worlds and warns against assuming that they are all the same. On the other hand, it is not too specific in prescribing a course of action. I shall argue that some of the most important phenomena of biology and cognition arise from general adaptive strategies akin to Annan’s, empty as they may appear to be of any specific expert knowledge. Although such strategies as listening and looking are not fine-tuned to any particular environment, they may nonetheless be effective in any environment that has certain weak regularities hidden among all the complexities. I shall suggest that not only are they effective, but, further, they are integral to any explanation of life and culture as we witness these on Earth.

安南的战略有它接受的有很多的乘载世界的力量，并警告不要假定它们都一样。另一方面，它不是行动的在课程规定得太具体。我应 ar 古道，一些最重要的生物学和认知现象源于与安南的一般自适应策略，空作为他们可能显示为任何特定的专业知识。虽然这种战略作为听和看起来不微调到任何特定的环境，他们可能仍将有某些薄弱的海况 larities 之间所有的复杂性隐藏任何环境中有效。我会建议，不只是他们有效的但进一步，他们是任何解释的生活和文化不可或缺的一部分，当我们目睹这些在地球上。

The new word ecorithm that I use to encapsulate these ideas derives from the word algorithm and the prefix eco-. An algorithm is simply any well- defined procedure. It is derived from the Latinized transliteration Algoritmi of the name of the mathematician Al-Khwārizmī, who worked in the House of Wisdom in Baghdad in the ninth century and authored an influential book on algebra. I invoke the word algorithm intentionally. In the domain in which it is most widely used, namely computer science, the standards of explicitness—of what is considered well defined—are high. In the words of computer scientist Donald Knuth, “Science is what we understand well enough to explain to a computer. Art is everything else we do.”2 I want to discuss evolution, learning, and intelligence in terms of algorithms that are unambiguous and explicit enough that they can be “explained to,” and hence simulated by, a computer. The prefix eco-, from the ancient Greek word oikos meaning household or home (and which evokes the word ecology), signals that we are interested in algorithms that operate in complicated environments, especially environments that are much more complex than the algorithm itself. There is no contradiction in this. While the algorithm has to perform well in a complex environment, about which it has little knowledge initially, it has a chance of doing so if it is allowed to interact extensively with the environment and learn from it.

新的单词 ecorithm，用来封装这些想法源自词算法和前缀生态-。算法是简单任何定义的过程。这被来自拉丁化 Algoritmi 的音译名称的数学家 Al Khwārizmī，在第九世纪在智慧的房子在巴格达工作并撰写了代数上有影响力的书。我故意调用 word 算法。在域中，它最广泛，即计算机科学、 明确的标准 — — 被认为是很好定义的 — — 很高。计算机科学家 Donald Knuth 的话说，"科学是我们充分理解的解释到计算机。艺术是我们做的一切。2我想要讨论演变、 学习和智力方面都毫不含糊和不够明确，他们可以"解释到，"，并因此由计算机模拟的算法。前缀生态-，从古希腊词 oikos 意味着家庭或家庭 (和，唤起词生态)，信号，我们很感兴趣在复杂环境中，尤其是比算法本身更复杂的环境中操作的算法。还有这没有矛盾。虽然该算法具有履行好在复杂环境中，而它最初，亦少了解它有机会这样做，如果它允许广泛与环境交互和从中吸取教训。

Within the realm of computation I make the following distinction. Algorithms as traditionally studied in mathematics and computer science are designed to solve instances of particular problems, such as solving algebraic equations or searching for a word in a text. All the expertise they need for their success is encoded in their own description by their designer. For example, Euclid in his textbook The Elements describes an elegant algorithm for finding the greatest common divisor of two numbers. (The greatest common divisor of 30 and 42 is 6.) His algorithm is correct and efficient in a specifiable sense even for arbitrarily large numbers. Its exact behavior on all pairs of numbers is entirely predictable, and no doubt foreseen by Euclid.

计算的范围内做以下的区别。作为传统算法在数学和计算机科学为了解决特定的问题，如代数方程组或搜索词在文本中的实例。他们为他们的成功需要的所有专门知识是由他们的设计师在她们自己的描述编码的。例如，欧几里得在他的教科书元素描述了优雅的算法求最大公因数的两个数字。(30 和 42 的最大公因数是 6)。他的算法的正确性和有效性宝山钢铁股份来说甚至对于任意大的数。对所有的数字对其确切的行为是完全可以预见，并按照欧几里得的设想无疑。

Ecorithms are special algorithms. In contrast with those designed to solve specific mathematical problems, these operate in environments that are not fully known to the designer, and may have much arbitrariness. Nevertheless, ecorithms can perform well even in these environments. While their success is foreseeable, the actual course they take will vary according to the environment.

Ecorithms 是专门的算法。与那些旨在解决具体的数学问题，这些操作中的环境到设计器中，完全不知道，可能有很大的任意性。然而，ecorithms 可以执行好，即使在这些环境中。而可以预见的是，他们的成功，他们实际的路线将环境而异。

The requirements that such an algorithm must meet to offer a plausible explanation of a natural phenomenon, such as biological evolution, are quite onerous. In particular, the algorithm must achieve its goals after a limited number of interactions and with the expenditure of limited resources. The concept of ecorithms and the general model of learning in which they are embedded, which I call probably approximately correct (or PAC) learning, insist on such quantitative practicality. The phenomena that they seek to ex- plain are some of the most familiar to human experience: learning, resilience, and adaptation. I argue that broader phenomena still, in particular evolution and intelligence, are also best understood in these terms.

这种算法必须满足提供一个合理的解释的一种自然现象，例如生物进化的要求是相当繁重的。尤其是，该算法必须实现其目标后为数有限的交互和资源有限的开支。Ecorithms 的概念和一般模型的学习，他们嵌入，我称之为可能大约正确 (或 PAC) 学习，坚持这种定量的实用性。他们找来前平原的现象是一些最熟悉的人类经验: 学习、 适应性和适应。我认为，更广泛现象仍然，在特定的演化和情报，也最好理解在这些条款。

Evolution in biology is the idea that life forms have changed over time, and that these changes have resulted in the organisms seen on Earth today. Although closely associated with Charles Darwin, the roots of the idea reach back to antiquity and the recognition of evident family resemblances among the various animal and plant species. In more recent history, Charles Dar- win’s grandfather, Erasmus Darwin, wrote a treatise, Zoonomia; or, The Laws of Organic Life, arguing for this idea in the 1790s. This view was widely debated and controversial. William Paley, in a highly influential book, Natural Theology (1802), argued that life, as complex as it is, could not have come into being without the help of a Designer. Numerous lines of evidence have become available in the two centuries since, through genetics and the fossil record, that persuade professional biologists that existing life forms on Earth are indeed related and have indeed evolved. This evidence contradicts Paley’s conclusion, but it does not directly address his argument. A convincing direct counterargument to Paley’s would need a specific evolution mechanism to be demonstrated capable of giving rise to the quantity and quality of the complexity now found in biology, within the time and re- sources believed to have been available.

生物进化是生命形式已随着时间的推移，这些变化已经造成今天看到地球上的生物的想法。虽然与查尔斯 · 达尔文密切相关，这个概念的来源到达回到上古和明显的家族相似性，各种动物和植物物种间的识别。在更近的历史，查尔斯 Dar 赢祖父，伊拉斯谟达尔文写了一篇论文，动物学 》;或者，法律的有机生命，在 1790 年代争论这一想法。这一观点被广泛和有争议的辩论。William Paley 中极具影响力的书，自然神学 (1802)，辩称生活，一样复杂，因为它是不可能产生之中没有一个设计师的帮助。许许多多的线索已经成为在地球上现有的生命形式确实是相互关联和事实上已经说服专业生物学家，两个世纪以来，通过遗传学和化石记录，可用。这一证据矛盾佩利的结论，但它不能直接解决他的论点。组织直接反驳到佩利的会需要一个具体演变机制来证明能产生的数量和质量现在发现在生物学中，时间和稀土来源据说可用范围内的复杂。

The main contribution of Charles Darwin was, of course, exactly so motivated.3 He posited the outlines of an evolution mechanism with two primary parts, namely variation and natural selection, that he argued was sufficient to explain biological evolution on Earth without a Designer. In its simplest form, the theory of natural selection asserts that each organism has some level of fitness in a given environment and that it is capable of producing a range of variants of itself as its progeny. It then attributes evolution to the phenomenon that among the variants, individuals that have characteristics that constitute greater fitness will have a higher probability of having descendants in later generations than those with less fitness.

查尔斯 · 达尔文的主要贡献是，当然，正是这样 motivated.3 他假定的轮廓演化机制与两个主要部分，即变异和自然选择，他认为是不足以解释生物进化对地球上没有一个设计师。在其最简单的形式中的自然选择理论断言每个有机体有某种程度的健身在一个给定的环境中，它是能够生产各种变体本身作为其后代。它然后属性演变到这一现象，不同变异类型，有构成较大的适应性的特点的个人将概率较高的后代在后世比那些较少的健身。

Among biologists there is broad consensus that Darwin’s theory is essentially correct. Biochemical descriptions of the basis of life provide a concrete language in terms of which the actual evolutionary path taken by life on Earth may one day be spelled out in detail and explained. At present there are many gaps in our knowledge. The relationship between the DNA (the genotype) and the behavior and physiology of the organism (phenotype) to which it belongs is little understood. In spite of this, over the last 150 years Darwin’s theory has become the central tenet of biology by virtue of substantial other evidence. Most recently, DNA sequencing has given incontrovertible experimental confirmation for the proposition that the varied life forms found on Earth are genetically related. Nothing that I will say here is intended or should be interpreted as casting doubt on this proposition. However, it remains the case that Darwin presented only an outline of a mechanism. It is not specific enough to be subject to a quantitative analysis or to a computer simulation. No one has yet shown that any version of variation and se- lection can account quantitatively for what we see on Earth. There is much that needs to be explained. Evolution has found solutions to many difficult problems that are of value to life on Earth. These include, among many others, locomotion, vision, flight, magnetic navigation, and echo location. Hu- mans have managed to find artificial solutions to these physical challenges only after enormous effort.

是生物学家达尔文的理论是基本上正确的广泛共识。生化描述的生活的基础提供一个具体的语言，即采取的生活在地球上的实际的进化路径可能有一天会详细地阐明和解释。目前有很多差距在我们的知识。DNA (基因型) 的行为和生理的有机体 (表现型) 它属于之间的关系是甚少。尽管这样，在过去 150 年达尔文的理论已经成为生物学凭借坚固的中心原则其他证据。最近，DNA 测序已经无可辩驳实验确认为在地球上发现的各种的生命形式的基因相关的命题。我会在这里说的什么都不有意或应被解释为对这一命题产生怀疑。然而，它仍然是达尔文案例仅概述了一种机制。它不是足够具体而无法进行量化分析，或进行了计算机模拟。没有人还表现，任何版本的变化和评卷可以定量解释我们在地球上看到。有很多需要加以解释。已发现演变的对地球上的生命有价值的许多困难问题的解决办法。这些包括，还有许多其他的运动、 视觉、 飞行、 磁导航和回波定位。胡-芒已设法找到人工解决这些物理的挑战，只有经过巨大的努力。

The achievements of evolution are palpable and objectively impressive. The possibility remains that every version of variation and selection, as we currently understand these terms, would have needed a million times as long to yield existing life forms than is believed to have been available. Saying that evolution is a contest or even a struggle for life does not go far in explaining these facts. No theory is known that would explain how competition by itself leads to such spectacular achievements. Lotteries, singing competitions, and gladiatorial contests have not produced similar improvements or novelty. Evolution is a special kind of contest. How are we to go about understanding how this special contest, of whatever kind it is, has been able to produce the spectacular inventions that it has?

进化的成就是显而易见和客观上令人印象深刻。可能性仍然，每个版本的变化和选择，据我们目前了解这些条款，就需要有一百万倍为长放弃现有的生命形式，比相信已经可用。说进化是一场竞赛，或甚至奋斗终生不会远，在解释这些事实。没有一种理论是已知这就解释了如何通过本身的竞争导致这样辉煌的成就。彩票、 歌咏比赛、 和角斗没有产生类似的改进或新颖性。进化是比赛的一种特殊。我们去了解如何这次特殊的比赛，无论哪一种是，已经能够产生壮观的发明，它有如何?

The term evolution evokes many images—indeed almost all facets of the history of life on Earth. I will restrict attention here to the one primary question of how complex mechanisms can arise at all within the limited time scale and resources in which they apparently have. The numerous other questions that are widely discussed by evolutionary theorists I regard as secondary to this one. The advantages offered by sex to evolution have been much debated, but evolution was far along when sex arrived on the scene. The intellectual challenge of understanding how peacocks could have acquired their elaborate plumage was much troubling to Darwin. But again, peacocks came along late in the game. In short, what I seek to address is a gap between the general formulation of natural selection as currently under- stood and any demonstration that any specific mechanism can account for the biological evidence we see around us. Every scientific theory has a gap that leaves some question unexplained. Evolution is by no means unique in that respect. Having a gap is no fatal flaw. However, the natural selection hypothesis as currently formulated has the gaping gap that it can make no quantitative predictions as far as the number of generations needed for the evolution of a behavior of a certain complexity. I believe that the time is ripe for working toward filling this gap. And I believe computer science is the tool for doing it.

长期演进唤起许多图像 — — 确实，几乎所有方面的地球上生命的历史。我将限制到一个多么复杂机制的首要问题可能出现在所有有限的时间尺度和他们显然有的资源范围内的关注。广泛讨论了进化理论家的许多其他问题我认为是继发于这一个。提供按性别对进化的优势得到了辩论，但进化在性别赶到现场的时候远沿。了解如何孔雀可以获得其绚丽的羽毛的智力挑战是多令人不安的达尔文。但是，孔雀又晚在游戏中。总之，我寻求到地址是自然选择目前下总的措词的差距-站和任何具体的机制可以占我们看到我们周围的生物证据任何示范。每一个科学理论有缺口，不明原因的一些问题。进化不是唯一在这方面。有一个缺口是不致命的缺陷。然而，按目前的措词，自然选择假说是有大的差距，它可以使几代人所需的某些复杂性行为的演化数目没有定量预测。我相信时机已经成熟的努力，以填补这一空白。计算机科学是做它的工具。

This may be an unconventional claim, but I will argue that Darwin’s theory lies at the very heart of computer science. Darwin’s theory may even be viewed as the paradigmatic ecorithmic idea. One of computation’s most fundamental characteristics is the separation between the physical realization of a mechanism and its manifest behavior. This is equally true of Darwin’s theory. Although the fitness of a biological organism depends both on the bio- chemistry of the organism and on all the physical, chemical, and ecological factors present in its environment, the principle of natural selection makes no mention of biochemistry, physics, or ecology, and it incorporates no specific knowledge about the fitness of a particular species in a particular environment. We are driven to the almost paradoxical conclusion that organisms that perform at such a sophisticated level of expertise in physics, biochemistry, and ecology are the products of generic mechanisms that incorporate no such expertise. This striking contrast summarizes the basic challenge that ecorithms in general, and evolutionary algorithms in particular, need to overcome.

这可能是一项非常规的索赔，但我会说，达尔文理论计算机科学的核心在于。达尔文的理论甚至可视为聚合 ecorithmic 想法。计算的最基本的特征之一是其清单的行为与机理的物理实现的分离。这是理论的达尔文同样如此。虽然生物有机体的健身取决于有机体的生物化学和物理、 化学、 和生态因素目前在其环境中，自然选择原理的生物化学、 物理或生态，只字不提，它包含了在特定环境中某一物种的健身没有具体了解。我们被驱使到几乎是自相矛盾的结论，执行一级这种复杂的物理、 生物化学、 生态的专门知识的生物是纳入没有这种专门知识的泛型机制的产物。这鲜明的对比总结基本挑战，ecorithms 在一般情况下，和进化算法尤其需要克服。

Given the central role that Darwin’s theory now plays in biology, the following fact is more than a little disconcerting. From the first availability of digital computers many intelligent, curiosity-driven individuals have sought to simulate selection-based evolutionary algorithms in order to demonstrate their efficacy. These simulation experiments, carried out over more than half a century, have been disappointing, at least in my view, in creating mechanisms remotely reminiscent of those found in the living cell. In fact, these experiments are seldom quoted as corroborating evidence for evolution.

鉴于达尔文的理论现在在生物学中发挥中心作用，以下事实是更多比有些不安。从第一个数字计算机的可用性很多智能，好奇心驱使个人寻求模拟基于选择的进化算法，以证明其有效性。这些模拟实验，进行了超过半个世纪，一直令人失望，至少在我看来，在远程创建机制让人联想到那些发现在活细胞。事实上，这些实验是很少引用作为进化的佐证。

This failure cannot be ignored. It suggests that the natural selection hypo- thesis has to be refined somehow if it is to offer a more explanatory scientific theory. Further, the refinement will need to have a quantitative component that reflects the realities of the actual bounded numbers of generations, and bounded numbers of individuals per generation, that apparently have been sufficient to support evolution in this universe. That evolution could work in principle in some infinite limit is obvious and needs little discussion. But modern humans are believed to have existed for no more than about 10,000 generations and with modest population sizes for much of that history. Our predecessor species may have had not dissimilar statistics. Theories of evolution that assume unbounded resources for evolution, in generations or population sizes, or those that do not address this issue at all, cannot resolve the central scientific question of whether some instance of natural selection does fit the constraints that have ruled in this universe.

这次失败不能忽视。它表明，自然选择海波论文加以提炼某种程度上，是否它是提供一个更具解释力的科学理论。进一步，细化将需要有一个定量的组件，反映现实的几代人，实际有界数目和有界每一代人，显然已足以在这个宇宙中支持进化的个体数目。进化可以工作原则上在一些无限的限制明显，需要小小的讨论。但现代人类被认为已经存在的不超过约 10,000 后代并与适度人口规模，历史的大部分时间。我们的前任物种可能有没有什么不同的统计数据。进化的理论，假定无界的资源的演变，在几代人或人口大小，或那些不做根本，解决这一问题不能解决的核心科学问题的一些实例自然选择是否不适合已裁定在这个宇宙中的约束。

I am not the first to point out that there is a tension between the long time apparently needed for evolution and the limited resources that evidence from the physical sciences suggests have been available. No one was more aware of this tension than Darwin himself. In an attempt to find corroborating evidence for the long time scale he believed was needed for evolution, he looked to geology. In the first edition of On the Origin of Species he included an estimate of 300 million years for the time needed for erosion to have created the Weald formation in southern England.4 This estimate immediately came under fire from the scientific community. Darwin omitted it, and any other such estimate, from subsequent editions. William Thomson (later Lord Kelvin) and other authoritative physicists of his day derided Darwin’s estimate as impossibly too high even for the age of the Earth itself. Their arguments were based on applying the principles of physics as then understood to the question of the rate at which the Earth had been losing heat. This in- direct line of attack on his theory of evolution gave Darwin much reason for concern. He wrote, “Thomson’s views on the recent age of the world have been for some time one of my sorest troubles.”5 Kelvin’s final published estimate was as low as 24 million years.6 Physicists now estimate the age of the Earth, thankfully, to be much higher, about 4.5 billion years (and 13.8 billion years for that of this universe). Nevertheless, we still do not have a quantitative explanation of how life could have reached its current state even within this more extended period that is now allotted by the physicists, whether on the Earth or in the broader universe.

我不是第一个指出，显然进化所需的长时间之间的关系紧张，有限的资源，从物理科学的证据表明已有。没有一个人比达尔文本人更加意识到这种紧张关系。在试图找到确凿的证据，对于长时间尺度他认为需要进化，他看上去对地质。在第一版的物种起源 》 中他包括估计 3 亿年的侵蚀，在这一估计数立即遭到来自科学界的南部 England.4 创造了原野形成所需的时间。这一估计数立即来自科学界下火。达尔文省略它，和任何其他这类估计，从后续的版本。William 汤姆逊 (后来的开尔文勋爵) 和其他权威的物理学家，他一天的嘲笑达尔文的估计是不可能太高，即使对地球本身的年龄。他们的论点是基于原则作为物理，然后理解到，地球一直在下滑热率的问题。此行中直接攻击他的进化理论给达尔文带来了很多理由感到关切。他写道，"汤姆森的意见世界最近年龄有段时间我最痛的烦恼之一。"5开尔文的最终发布的估算是物理学家 years.6 2400 万现在估计地球的年龄，值得庆幸的是，要高得多，大约 45 亿年 (和 138 亿多年，这个宇宙) 的一样低。尽管如此，我们仍然没有如何生活就可能到达其当前状态即使在这个较长的时期，现在分配的物理学家，无论是在地球上或在更宽广的宇宙内龄我解释。

The theory offered here, of treating Darwinian evolution as a computational learning mechanism and quantitatively analyzing its behavior, is the only approach I know that addresses these questions explicitly. Previous mathematical approaches to evolution, such as those of population genetics, analyze the effects of competition on relative population sizes. For example, the famous Hardy-Weinberg principle from the early twentieth century shows that if reproduction is sexual and members of a population have two copies of each gene, as in humans, then diversity in the gene pool will be conserved in the following sense. If two variants of a gene exist in the population in a certain ratio and they are equally beneficial, then their ratio of occurrence in the population will converge to a stable value, with both variants continuing to occur. Analyses of relative population sizes such as this, however, do not address how more complex forms can come into being from simpler ones—this is the most fundamental question and the one that opponents of evolution usually target. One is not performing a service to science if one pretends to have a solution when one does not.

理论提供在这里，达尔文的进化论当作一种计算学习机制和定量地分析其行为，是我知道的唯一办法，明确解决这些问题。以前的数学方法演化中，如那些群体遗传学分析竞争对相对人口大小的影响。例如，从二十世纪初著名的哈迪-温伯格原理表明，繁殖性和人口的成员有两个副本的每个基因，对于人类来说，如果我们多样性的基因库中将保存在以下意义上。如果两个变种基因的存在在一定比例的人口和他们是同样有益，然后他们发生在人口中的比例会收敛到一个稳定的值，与这两个变种继续发生。这样，然而，相对人口规模的分析不能解决如何更复杂的形式可以进入正在从较简单的 — — 这是最根本的问题，并且是进化的对手通常目标。一个未执行科学服务如果一个假装有一个解决方案，当一个人不。

Advances in biology over the last half century have made concrete what needs to be explained in ways that were not known to the earlier pioneers of population genetics such as the eminent statistician Ronald Fisher. We now know that biological organisms are governed by protein expression networks. To understand evolution we need to have an explanation of how such complex circuits can evolve from simpler ones and maintain themselves in changing environments. The protein expression networks on which our bio- logy depends are known to have more than 20,000 genes, and the outputs they produce depend in a highly complicated way on the innumerably many possible input combinations. These circuits define how the concentration levels of the many proteins in our cells are controlled in terms of each other. We can seek to describe them mathematically. For example, the amount produced of our seventh protein may depend on the concentrations of three others—say, the third, twenty-first, and seventy-third. The dependence is something specific, perhaps f7 = 1.7x3 + 3.4x21 + 0.5x73, or more likely something else. But in any case it is some particular dependency f7(x1,..., x20,000) on all the available proteins and possibly on some additional parameters, such as temperature. Whatever this dependency f7 is, it will change during evolution if some other such dependency becomes more beneficial to the organism because of changing circumstances.

在过去的半个世纪的生物学研究进展取得具体需要什么不被人口遗传学等著名统计学家罗纳德 · 费雪的早期先驱的方面来解释。现在，我们知道生物有机体由蛋白质表达网络。要了解我们需要解释如何这样复杂的电路可以从简单的进化和维护自己在变化环境中的演化。我们生物-迟缓所依赖的蛋白表达网络已知有超过 20000 个基因和它们产生的输出在一个高度复杂的方式取决于无数许多可能的输入组合。这些电路定义如何将许多在我们的细胞中蛋白质的含量水平控制在彼此。我们可以寻求为数学上描述他们。例如，我们的第七届蛋白质产生的金额可能取决于三个别人的浓度 — — 说、 第三、 二十一、 第七十三。依赖是特定的也许 f7 = 1.7x3 + 3.4x21 + 0.5x73，或更有可能其他的东西。但在任何情况下它是一些特定依赖项 f7 (x 1，...，x 20，000) 上所有可用的蛋白质，可能对一些额外的参数，如温度。此依赖项 f7 不管是什么，它将改变在演化过程中如果一些其他依赖关系变得更有益于有机体由于不断变化的情况。

What an evolutionary theory must do is explain how these dependencies are updated during evolution. How long will it take to evolve to a new function f'7 if the environment changes so that the new function f'7 is better than the old f7? Of course, this only accounts for evolution with a fixed set of proteins. A successful theory must also explain the evolution of new proteins. I believe that this will need a similar kind of analysis but for a different kind of circuit.

进化理论必须做的是解释这些依赖项在演化过程中的更新方式。如果在环境发生变化，新的函数 f 7 优于旧 f7 进化到一个新的函数 f 7 需要多长时间?当然，这只占演化的一套固定的蛋白质。一个成功的理论也必须解释新的蛋白质的演化的过程。我相信，这将需要类似的分析，但对于一种不同的电路。

Over the last several decades it has emerged that there are computational laws that apply to the existence and efficiency of algorithms that are as striking as physical laws. These computational laws offer a powerful new view- point on our world that meets the challenge that the facts of biology lay down in regard to both evolution and learning. The laws that are most relevant to these phenomena are different from those that are the most useful for programmers of digital computers, and they need to be investigated separately. This will be our point of departure.

在过去几十年它涌现了有适用于存在和是一样引人注目的是物理定律的算法效率的计算法。这些计算的法律提供一个强有力的新视图点，对我们的生物学事实躺在进化和学习方面的挑战的世界。与这些现象最为相关的法律是不同于那些对于数字计算机程序员最有用，他们需要分别进行研究。这将是出发点的我们。

Nothing here is intended as the last word on any of the topics covered. The approach I propose needs extensive development both internally and in interaction with the experimental sciences it relates to. The idea that mathematical equations are useful for expressing the laws of physics, that laboratory experiments can uncover the facts of chemistry, and that statistical analyses in the social sciences yield clues about causation are all widely appreciated. But the notion that natural phenomena can be understood as computational processes or algorithms is much more recent. I have no doubt, however, that this algorithmic viewpoint is poised to take its place among the more familiar arsenal of weapons used for uncovering the secrets of nature. I hope to offer here a glimpse of how this algorithmic perspective will come to occupy a central position in science. First, however, we must turn to the questions of the nature and scope of computational processes in general.

这里没有旨在作为对任何主题的最后一句话。方法我们提出需要广泛发展，目的内部和互动与实验的科学，它涉及到了。所有广为人数学方程可用于表示物理定律的实验室的实验可以揭露事实的化学，和在社会科学统计分析线索关于因果关系的想法。但自然现象可以被理解为计算过程或算法的概念是近得多。我有毫无疑问，然而，这个算法的观点正准备采取它的位置更熟悉的阿森纳的武器用于揭示大自然的奥秘。我希望能在这里让我们看到了这个算法的角度会占据在科学中的中心地位。第一，但我们必须把问题的性质和范围的计算过程一般。

# Chapter Three The Computable

Not everything that can be defined can be computed.

Computer science is no more about computers than astronomy is about telescopes. EDSGER DIJKSTRA

不是一切都可以定义可以被计算。 计算机科学是没有更多关于计算机比天文望远镜。EDSGER DIJKSTRA

## 3.1 The Turing Paradigm

In retrospect, humans have been remarkably uncurious for too long about information processing. Animals take complex inputs when seeing, smelling, touching, or hearing, and then produce behaviors that depend in complicated ways on these inputs. Human behavior can be even more perplexing and hard to understand. Phenomena like these we can observe every day. It would seem natural to wonder: Just how do living organisms process in- formation and decide what to do? Curiously, until recent decades little intellectual effort has been put into understanding this question. To be fair to our predecessors, however, it is clear that, until recently, anyone attempting to study information processing would have been stymied by a fundamental impediment—no way was known of even formulating the question.

现在回想起来，人类已为太久明显不在乎于信息处理。动物采用复杂的输入，当看到、 嗅到、 触摸，或听到，然后产生以复杂的方式取决于这些投入的行为。人类行为可以更令人费解和难以理解。这样的现象我们可以观察到每一天。这会似乎很自然不知道: 只是如何做生物过程中形成和决定该怎么办?奇怪的是，直到最近几十年来小知性的努力已了解这一问题。为了公平起见，我们的前辈，但是，很明显，直到最近，任何人试图研究信息处理将一直受阻于一个基本的障碍 — — 绝不人所共知的甚至制订问题。

This only changed in the 1930s, when Alan Turing published a mathematical paper, “On Computable Numbers, with an Application to the Entscheidungs problem,” that inaugurated one of the most significant scientific revolutions in history.1 The Entscheidungs problem (or decision problem, in English) refers to a question raised by mathematician David Hilbert in 1928 concerned with deciding the validity of statements in mathematical logic. However, in his paper Turing went far beyond answering this one question. He formulated a notion that has changed how we view the world. Through its technological impact, this notion has changed how we live. His discovery was that computation, or the execution of step-by-step procedures for processing information, could be defined and studied systematically. Since that time we have been on a recognizable track toward understanding what such procedures can and cannot do. That is to say, we have come to understand computation. We have also been exploiting that understanding to produce technology, but technology is not my concern here.

这只改变 20 世纪 30 年代，当 Alan Turing 发表数学论文，《 论可计算的数字，与 Entscheidungs 问题，应用"落成的之一 history.1 Entscheidungs 问题 (或决策问题，在英语中的) 中最重大的科学革命是指数学家 David Hilbert 在 1928 年与决定的声明在数理逻辑的有效性有关的质询。然而，在他的论文图灵远远超出回答这一问题。他制定了一个概念，改变了我们对世界的看法。通过其技术的影响，这种观念已经改变了我们的生活方式。他的发现是，计算或用于处理信息的分步过程的执行，可以定义和系统地研究了。自那时以来，我们一直以辨认方向理解这种程序可以做什么和不能做什么。即是说，我们来了解计算。我们也利用了这种理解来生产技术，但技术不是我在这里所关注。

The technical concept of computability makes an important distinction: It is one thing to specify, even unambiguously, what result you expect from a computation for every input of data. It is quite another to specify a step-by- step computation that gets you there. The difference is not immediately apparent. Nevertheless, Alan Turing proved that there exist problems for which there is no ambiguity as to what result is desired, but for which there is no set of step-by-step instructions that will get you the right result for every in- put. This was a stunning finding. Research over the past several decades has developed a rich science for making even finer distinctions, particularly with regard to efficiency. It turns out that there are also problems that are not computable efficiently enough to be practical, even if in principle they can be computed. That fact poses its own problems: We want computations not only to exist in principle, but also to deliver answers within a reasonable period of time. To obtain the result we should not have to wait for months, or years, or until after our galaxy has ceased to exist.

可计算性的技术概念让一个重要的区别: 一件事，若要指定，甚至毫不含糊地，什么是结果不是你期望从一个计算对于每个输入的数据。它完全是另一个用于指定那里获取你的步计算。的差异并不是显而易见的。然而，Alan Turing 的证明了，存在的问题，现在想要什么结果没有歧义，但是是没有一套就可以正确的结果，每个在付诸表决的分步指导。这是一个惊人的发现。在过去几年的研究已发展丰富科学制作更精细的区分，特别是在效率方面。原来也有问题，不是可计算的有效足够要踏实，即使在原理可以计算。事实提出自己的问题: 我们想要计算不只是存在于原则，同时也是在合理的时间内把答案。要获得的结果，我们不应该在我们的星系后等待数月或数年，或已不再存在。

These laws of computation apply to all algorithms. Because ecorithms are algorithms, though of a special kind, they too must follow the same basic laws as computation in general. This new science of the ultimate limitations on the possibility and the efficiency with which computations for learning and evolution can proceed offers a fundamental new approach to understanding these phenomena of learning and evolution, because, regardless of how they are implemented—in silicon, DNA, neurons, or something else entirely—there are some ultimate logical laws that limit what these mechanisms can do.

计算这些法律适用于所有的算法。因为 ecorithms 算法，虽然的一种特殊，他们也必须遵循相同的基本定律作为计算一般。这种新的可能性和效率，可以继续学习和进化计算的最终限制科学提供基本的新方法，对于理解这些现象的学习与进化，因为，不管他们如何实现 — — 中硅、 DNA、 神经元，或别的东西完全 — — 有一些最终的逻辑法律限制这些机制能做些什么。

Turing’s paper contained several ingredients that are now seen as fundamental to the study of computation. First, he described a model, now called the Turing machine, that captures the phenomenon he was attempting to de- scribe, namely that of mechanistic step-by-step procedures. Second, he proved a strong possibility result for what can be achieved on his model. In particular, he showed how to design a universal Turing machine that is cap- able of executing every possible mechanical procedure. This universality property is what enables computer technology to be so pervasively useful, and would be utterly astonishing were it not so commonplace now by virtue of its effectiveness. Third, Turing also proved a strong impossibility result, that not all well-defined mathematical problems can be solved mechanically.

图灵的文件载有几个成分，现在见到的基础，计算的研究。首先，他描述了一种模式，现在被称为图灵机，捕捉到他正在试图向德抄写员的现象，即是机械论的分步过程。第二，他证明了他的模型上可以取得的成就很大的可能性结果。尤其是，他展示了如何设计通用图灵机是帽-能执行每个可能的机械过程。此普遍性属性是一种使计算机技术，所以普遍有用，和将完全令人惊讶它并非是司空见惯的事情现在凭借其效力。第三，图灵也证明强不可能结果，可以机械地解决不良好定义的所有的数学问题。

Turing’s impossibility result is as striking as universality is on the positive side. It is concerned with the problem of predicting, for an arbitrary computer program and an input for it, whether that program started on that in- put will ever halt its computation after a finite number of steps, as opposed to getting stuck in a loop in perpetuity. This so-called Halting Problem is well defined. Once we specify a language for expressing the programs there is no ambiguity at all about what would and what would not constitute a solution to it. It would be good to be able to tell ahead of time whether a computer program will get stuck in a perpetual loop. Yet, as Turing showed, it cannot be solved in all cases by any Turing machine.2 We will never be able to solve this problem routinely.

图灵的不可能性结果令人震惊的普遍性是积极的一面。是否该程序开始在那放在过将停止其计算步骤，而不是被困在一个循环中在永久有限数目后的，它是与问题的预测，为任意计算机程序和输入有关吧。这所谓的停机问题是清楚的。一旦我们指定一种语言表达的程序是不存在多义性在所有关于什么会和什么不会构成对它的解决方案。它一定要能够提前告诉计算机程序将陷入永久的循环。然而，正如图灵所表明的它不能解决在所有情况下由任何图灵 machine.2 我们将永远无法经常解决这一问题。

Many of the foremost thinkers of the early part of the twentieth century had wondered, somewhat informally, whether mechanical procedures existed for resolving all mathematically well-posed questions. Some, such as the philosopher Bertrand Russell and the mathematician David Hilbert, were optimistic. Turing’s discovery that one could define precisely what such an assertion meant, and then prove that such a statement was false, had revolutionary implications. The shock of this is still taking its time to permeate the community of the educated.

首先是思想家的二十世纪之初的很多人一直在想，有些通俗地讲，机械的程序为解决所有的数学上适的问题是否存在。一些哲学家伯特兰 · 罗素等数学家 David Hilbert 是乐观。图灵的发现一个可以定义正是什么这种说法的意思，，然后证明这种说法是假的产生了革命性的影响。这冲击还处于它的时间来渗透，受教育者的社会。

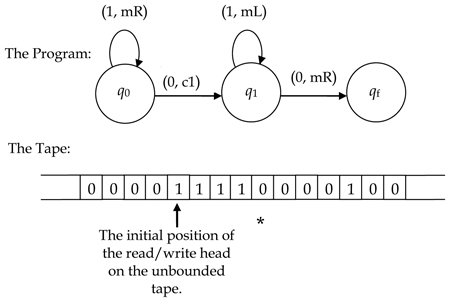


Figure 3.1 An example of a simple Turing machine. The diagram at the top de- scribes the program that controls the machine. The input is the sequence of 0s and 1s on successive squares of the tape. The machine has three states q0, q1, and qf . It starts in state q0 and with the read/write head on the square pointed to by the thick arrow. If the machine is in state q0 and the symbol under the head is 1 (as it is initially in this example), then the path indicated by the arrow out of the q0 node with label starting with a 1 will be taken, in this case the arrow labeled (1, mR) with endpoint q0. Executing this (1, mR) will result in the contents of the square being unchanged and the head moving one square to the right. The end- point of the arrow indicates that the next state will be q0 again. An arrow labeled (1, mL) would mean the same except that the head moves to the left. An arrow labeled (1, c0) would mean that the square is changed from 1 to 0 and the head does not move. The labels (0, mR), (0, mL), and (0, c1) have analogous meanings and apply when instead the symbol under the head is 0. The computation halts if and when a final state qf is reached. The reader may verify by working through this example that, eventually, when the read/write head reaches the 0 at the \* sign, the machine will change the 0 there to a 1 and change the state to q1, then move the head back finally to the starting position, and then halt in state qf. (Note that we can obtain an example of a machine that never halts on this input by changing the (0, mR) arrow from q1 to go to q0 rather than to qf .)

图 3.1 简单图灵机的例子。在顶部的德经学家图控制机器的程序。输入是磁带的 0 和 1 的连续正方形上的顺序。这台机器有三种状态 q0 和 q1，qf。它开始在状态 q0 和读/写头粗箭头所指向的广场上。如果这台机器是在状态 q0 和头下面的符号是 1 (因为它最初是在这个例子中)，然后由 q0 节点了箭与标签从 1 开始的路径将采取，在这种情况下的箭头标记为 (1，mR) 与终结点 q0。执行此 (1，先生) 将导致在广场固定不变的内容和头移动一个广场向右。箭头的终点指示下一个状态将 q0。箭头标记为 (1，毫升) 将意思相同，只是头向左移动。箭头标记为 (1，c0) 将意味着广场从 1 更改为 0 和头部不动。标签 (0，mR)，(0，毫升)，和 (0，c1) 有类似的含义和适用时相反的符号下头是 0。当 qf 达到最终的状态时，将暂停计算。读者可以通过工作通过这个例子来验证，最终，当读写头到达在 0 \* 标志，机器会将那里的 0 更改为 1 和状态更改为 q1，然后移头回到最后的起始位置，然后在停止状态 qf。(请注意，我们可以获得从来没有停止对此输入通过改变 (0，先生) 机的一个例子从 q1 去 q0，而不是 qf 箭头。)

Important as the three particulars of Turing’s paper are—namely Turing machines, universality, and non-computability—they become even more significant when viewed as an instance of a general class of what I call a Turing triad: an unambiguous model of computation that captures some real-world phenomenon (mechanical calculation in Turing’s specific case), and both possibility and impossibility results about that model. Learning, evolution, and intelligence are all manifestations of computational processes. As realized in nature, they may be subtle and operate near the limits of computational feasibility. We may need a correspondingly sophisticated understanding of computation before we can unravel their secrets. My strategy for shed- ding light on them will be to seek Turing triads for these phenomena also.

图灵的论文的三个细节很重要 — — 即灵机、 普遍性和非计算性 — — 他们变得更为重要时视为实例一般称之为图灵黑社会类: 一种毫不含糊的捕获一些现实世界现象 (在具体案例中图灵的力学计算)，可能性和不可能性结果关于该模型的计算模型。学习、 进化和情报是计算过程的各种表现。在自然意识到了，他们可能是微妙的和操作接近极限的计算的可行性。之前我们可以揭开他们的秘密，我们可能需要计算相应的先进理解。我对他们的棚顶光的策略将寻求这些现象的图灵黑社会也。

3.2 Robust Computational Models

The reader may have noticed that in the previous section there was an unexplained leap. The assertion that the Halting Problem was not computable by any Turing machine was identified with the claim that it was not computable by any conceivable mechanical procedure. To justify this leap, we will need a notion known as the robustness of models under variation, one of computer science’s deepest and most fortunate mysteries.

读者可能已经注意到，在上一节是不明原因的飞跃。它不是可计算的索赔由任何可以想象的机械过程发现停机问题不是由任何图灵机可计算的说法。为了证明这一飞跃，我们将需要一个称为下变化，计算机科学最深切和最幸运的谜团之一模型的鲁棒性的概念。

We have seen that an essential ingredient of the Turing methodology is that of defining a model of computation that captures a real-world phenomenon, in this case that of mechanical processes, including those that no one had (or has yet) envisaged. That last part is crucial: With his machine, Turing aimed to capture all processes a human could exploit while performing a mental task that can be regarded as mechanical as opposed to requiring creativity or inspiration. The audaciousness of the attempt has attracted many who would prove Turing’s machine insufficient to the power Turing claimed for it. However, when different individuals have tried to define their own notions of mechanical processes in hopes of creating models of greater power, all the models they have devised—no matter how different they may seem—could be proved to have no greater capabilities than those of Turing machines. For example, having two tapes, or five tapes, or a two-dimension- al tape adds no new power. Similarly, allowing the program to make random decisions, or transitions that have the parallelism suggested by quantum mechanics, also adds no new capabilities. Extensive efforts at finding models that have greater power than Turing machines, but still correspond to what one would instinctively regard as mechanical processes, have all failed. Therefore there is now overwhelming historical evidence that Turing’s notion of computability is highly robust to variation in definition. This has placed Turing computability among the most securely established theories known to science.

我们已经看到图灵方法论的一个基本要素是，定义捕获真实世界现象的计算模型，在这种情况下，机械加工工序，包括那些没有人了 (或尚未) 设想。最后一部分是关键: 与他的机器，图灵旨在捕获所有的进程，人类可以开发的同时，进行可以视为一样机械而不是要求创造力或灵感的脑力劳动。尝试的无畏吸引了很多人到图灵宣称因为它的力量不足的图灵机。然而，当不同的个体有试图定义自己的期望创建模型的更大的权力，他们给出的所有型号的机械加工过程的概念 — — 无论它们看起来有多么的不同 — — 可以证明有没有更强大的功能，比那些图灵机。例如，有两个磁带或五个磁带，或两个维度铝磁带添加任何新的权力。同样，允许程序使随机决定或已提出量子力学中的并行性的过渡还没有新的功能。广泛努力在寻找模型有更大的权力，比图灵机，但仍然对应于一个本能地认为作为机械过程，都被失败。因此有现在大量历史证据，图灵可计算性概念是高度变异在定义中的鲁棒性。这使图灵可计算性之间科学上已知的最安全地建立理论。

This robustness under variation of the model offers the fundamental key and launching pad for our study here. For learning and evolution, robust models are as indispensable as they are for general computation. Without this robustness the value of any model or theory is questionable. We are not interested in properties of arbitrary formalisms. We want some assurance that we have captured the characteristics of some real-world phenomenon. Robustness of models is the only known source of such assurance.

这下变化模型的鲁棒性提供基本键和我们研究这里的跳板。为学习和进化，鲁棒模型是一样不可或缺，因为它们是通用计算的。没有此鲁棒性的任何模型或理论值是值得怀疑。我们不感兴趣的任意形式的属性。我们想要一些保证，我们抓获了一些现实世界现象的特征。模型的鲁棒性是这种保证的唯一已知的来源。

The discovery of the notion of computability constituted a new approach to discovering truths about the world. The logician Kurt Gödel generously acknowledged that computability theory “has for the first time succeeded in giving an absolute definition of an interesting epistemological notion, i.e., one not depending on the formalism chosen.”3 What can be computed does not change as one varies the details of the model. In later chapters, I shall try to persuade the reader that, for the same reason, analogous absolute definitions should be sought also for other notions, and in particular learning and evolution.

发现的可计算性的概念构成发现真相关于世界的新方法。逻辑学家库尔特 · 哥德尔慷慨承认那可计算性理论"已首次成功地给予绝对的定义的一个有趣的认识论概念，即，一个不取决于选择的形式主义."3 什么是可以计算不会更改其中一个不同的模型的详细信息。在后面的章节，我会尽量说服读者，为同样的原因，类似的绝对定义应寻求也为其他的概念，特别学习和进化。

There is, of course, no reason to believe that for every notion for which there is a word in a dictionary there exists an absolute definition, or a robust computational model that captures its essence. Indeed, computability, learnability, and evolvability may be among the few. For most other notions no such robust computational models are known, and although robust models may be discovered one day for some, for the rest no such models may exist at all. The question of whether notions such as free will or consciousness can be made theoryful by the algorithmic method pursued here hangs, I believe, on whether robust computational models can be found for them.

当然，这也是没有理由相信，对于每个概念，还有一个词在字典中都存在一个绝对的定义或一个鲁棒的计算模型，抓住其本质。事实上，可计算性、 易学性和进化可能在几个国家。对于大多数其他概念没有这种鲁棒的计算模型已知的和尽管鲁棒模型可能会发现一些的一天，对于其余没有这种模式可能存在根本。是否如自由意志或意识的概念可以由 theoryful 算法的方法的问题追求这里挂起，我相信，能否为他们找到鲁棒计算模型。

## 3.3 The Character of Computational Laws

Turing’s contributions amounted to more than a series of specific discoveries; they provided a new way of pursuing science. In this, his importance demands comparison with that of Isaac Newton. Newton’s influence on physics is without parallel, not because he described gravity or made any other particular discovery, but because it was through his work that it became accepted that the physical world obeys laws that can be described by mathematical equations, and that solving these equations could yield accurate predictions of what will happen in the future. Newton’s theories not only had the immediate generality that they applied very broadly to mechanical systems. They had a higher level super generality in that they offered a blueprint for developing theories for fields that had yet to be conceived. Physicists have followed this lodestone of expressing physical laws by mathematical equations ever since. Electromagnetic theory, general relativity, and quantum mechanics are not implied by Newton’s mechanics, but they follow the same intellectual pattern: physical laws expressed as mathematical equations. In this sense, equations offered the wizardry that enabled successive generations of physicists to achieve an understanding of the physical world beyond that of which previous generations could have dreamed. Since the seventeenth century physics has been transformed several times as far as the range of phenomena that it could explain. Even as the particular discoveries of Newton have been superseded, physics is still being pursued with a methodology re- cognizably similar to that used by Newton.

图灵的捐款共计更多比一系列特定的发现;他们提供从事科学研究的新的方法。在这方面，他的重要性要求比较与艾萨克 · 牛顿。牛顿的物理学的影响没有平行，不是因为他描述重力或作出任何其他特别的发现，但因为它是通过他的工作，它成为了接受物理世界服从法律，可以用数学方程描述和，求解这些方程可以产生准确的预测，在未来会发生什么。牛顿的理论不仅有立即的一般性原则下，他们非常广泛适用于机械系统。他们有较高水平的超级共性，他们提供发展理论尚未被构想的字段的蓝图。物理学家已经跟随这天然磁石自从表达物理定律的数学方程。电磁理论即广义相对论和量子力学不暗示由牛顿力学，但他们遵循相同的智力模式: 以数学方程表示的物理定律。在这个意义上，方程提供了启用一代物理学家实现理解物理世界的前几代人梦到在那之外的魔术。自十七世纪以来物理学已经多次到它无法解释的现象的范围。即使如已取代牛顿的特别发现，物理是仍在继续进行与方法论 re-cognizably 相似，使用由牛顿。