VLATKO VEDRAL

DECODING REALITY

the universe as quantum information

'By turns irreverent, erudite and funny . . . A ripping good read' *New Scientist*

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The Universe as Quantum Information

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I would like to thank the departments of physics at the Universities of Oxford and Leeds, UK, and the National University of Singapore who have provided me with a great environment encouraging scientific debate and giving me a better opportunity to communicate science to a wider audience.

Writing is a very solitary exercise and it has been a great pleasure to be able to talk about some aspects of this book to a 'live' audience. Those who attended my various Café Scientifique talks and similar occasions will recognize some material from my talks in here. I am a great believer in taking science out of the University confines and onto the streets. That is where it all started—in the Ancient Greek agorae of Socrates—and that's where it ultimately belongs. I hope that the book preserves some traces of this 'streetwise' style of communicating science.

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My wife Ivona, my sons Mikey and Leo, and my daughter Mia have suffered a great deal in the past two years. They are everything I have—the alpha and the omega—and without them, there would be no reality to decode. I hope to make up for the lost time in the years to come.

PROLOGUE

In autumn 1994, while a final year undergraduate student in London, sorting through my reading material for the forthcoming term, I found three words that would have a profound effect on my future. These three words got me thinking again about questions that I have encountered both in life and in physics. At the time I wasn't exactly sure what they meant, but steadily things started to make sense.

Every child is at some point exposed to various rules (laws and principles) that seem to govern the functioning of the Universe and everything in it. Newton's laws in physics, the photosynthesis cycle in biology, rules of grammar in French, the law of supply and demand in economics, the list just goes on. As a child I remember feeling a little lost and bewildered by these rules that I was required to learn verbatim and just attributed their origin to a magician's trick, something my teacher pulled out of a hat. Further along in life, as our senses and our understanding of the world around us develops, these 'tricks' don't seem quite so intimidating. We are better able to deconstruct them and find that many are not so dissimilar after all. Then at some point, after exploring a sufficient number of these rules across different disciplines, we are in a position to begin speculating on their connection and whether there is a little master book of magic which governs them all. It is this bigger picture that now drives me and many others. Whatever walk of life you come from, the question remains the same: is the reality that we see around us just made up from a seemingly random collection of unrelated rules and events or is there a common underlying thread from which these all derive?

From the dawn of civilization, some of our most inquisitive minds have been pursuing this common thread. By linking together the rubbing of rock on rock or wood on wood we have been able to create fire. By linking together the falling of an apple to the orbits of planets, we have been able to fly to the Moon. By linking together our understanding of

molecules with engineering, we have been able to extend human life by successfully performing the vast array of bodily repairs. By linking together our understanding of human nature with communications technology, we have a global market for products and services regardless of the language we speak. Our attempts at understanding and linking different aspects of reality have clearly been very beneficial.

As we continue to further increase our understanding we expect this progress to continue. There is no doubt that any such future development will be based on how well we can interpret new information and connect what we have learned thus far. By continuing to create more connections we can develop more all-encompassing laws which we then in turn use to better understand and affect our reality. In other words, first we break down or decode what we see around us, just to then use this information to construct or encode a better, more well-connected, picture. The big question, of course, is how much can we connect—is it feasible that there is one ultimate law, one master magician's trick, that describes the whole Universe?

Within this discourse, surely the most exciting and fundamental question of all has to be: why is there a reality at all and where does it come from? In other words, before we can even speak about why things are connected, we need to ask ourselves why things exist in the first place. I will argue in this book that the notion of 'information' gives us the answer to both questions. Curiously, this makes information a far more fundamental quantity in the Universe than matter or energy, which is no mean feat in itself. If we look at reality in terms of 'bits of information', it is interesting that both the existence of reality and its inherent connectivity become completely transparent. Irrespective of whether you are a casual reader or a scientific researcher this has extraordinary implications for each and every one of us.

The three words that I read back in autumn 1994, which changed my perspective so markedly, were 'Information is physical'. The three words, in this order, stood out as the title of an amazing chapter in an otherwise obscure book, and over time made me realize that indeed maybe information is the

answer. After having spent the last 15 years convincing myself that it is, I now endeavour to spend the next 12 chapters convincing you likewise.

1
Creation Ex Nihilo: Something from Nothing

Every civilization in the history of humanity has had its myth of creation. Humans have a deeply rooted and seemingly insatiable desire to understand not only their own origins but also the origins of other things around them. Most if not all of the myths since the dawn of man involve some kind of higher or supernatural beings which are intimately related to the existence and functioning of all things in the Universe. Modern man still holds a multitude of different views of the ultimate origin of the Universe, though a couple of the most well represented religions, Christianity and Islam, maintain that there was a single creator responsible for all that we see around us.

It is a predominant belief in Catholicism, accounting for about one-sixth of humanity, that the Creator achieved full creation of the Universe out of nothing—a belief that goes under the name of *creation ex nihilo*. (To be fair, not all Catholics believe this, but they ought to if they follow the Pope.) Postulating a supernatural being does not really help explain reality since then we only displace the question of the origins of reality to explaining the existence of the supernatural being. To this no religion offers any real answers.

If you think that scientists might have a vastly more insightful understanding of the origin of the Universe compared to that of major religions, then you'd better think again. Admittedly, most scientists are probably atheists (interestingly, more than 95% in the United Kingdom) but this does not necessarily mean that they do not hold some kind of a belief about what the Creation was like and where all this stuff around us comes from. The point is that, under all the postulates and axioms, if you dig far enough, you'll find that they are as stumped as anyone else. So, from the point of view

of explaining why there is a reality and where it ultimately comes from, being religious or not makes absolutely no difference—we all end up with the same tricky question.

Every time I read a book on the religious or philosophical outlook of the world I cannot help but recognize many ideas in there as related to some ideas that we have in science. For example, the attitude of 'reductionism'—the fact that we try to reduce everything to a single simple cause—is common to both a religious and scientific way of thinking. While methods of investigation can vary, in the same way that in religion we reduce everything to a common deity, in science we strive towards a unifying theory of everything. In fact this inherent desire to reduce the number of unknowns is prevalent in almost everything we do. Why should this be the case?

Often there are two different reasons given for this natural desire to simplify. First is that we as humans have a very limited imagination and whichever medium we use to understand the world—be it science, religion, philosophy, or art—we will end up exploiting the same limited set of ideas available to us. In other words, even as we begin to describe reality, the ideas that we use are not so different from one another. As an eminent American psychologist, Abraham Maslow, points out, when your only tool is a hammer, every problem looks like a nail. The hammer in our case could be our natural urge to find simple cause and effect relationships. We humans thrive on reducing complexity, finding it more beautiful and more believable to summarize our whole understanding ultimately in terms of one principle (whether it is a single god or a single theory of everything).

It is also important to appreciate that our reality, i.e. our view of the Universe, might be different from the actual Universe itself. We create our reality through our understanding of the Universe and our reality is what is possible based on everything we know. If we heed Maslow's words then we already understand that we are invariably limited, and accept that whatever reality we generate may only ever be an approximation to what the Universe is really like. In this sense, it is somewhat inevitable that as we build and then look to explain our reality, the singular thesis is

somehow embedded within this; it is just a very comfortable notion for us to deal with.

Coupled to this, the second reason is that humans are also social beings. Artists, scientists, clergy, and the lay public all exchange ideas with one another, ideas which then feature in each other's work as we try to better understand our Universe, and generate our picture of reality. Notions of beauty and truth in one area inevitably affect ideas in another. With so many compelling arguments, it is perhaps no wonder then that we all follow more or less a similar road.

According to the German philosopher Ludwig Feuerbach, 'Man first unconsciously and involuntarily creates God in his own image, and after this God consciously and voluntarily creates man in his own image'. If we take God as synonymous to reality, then reality and Man's perception of it are, in fact, inseparable. Man creates reality and then uses reality to describe himself. As we strive to reduce complexity, it is again unsurprising that we try to build our reality on the simplest possible causes.

A more optimistic view as to why our ideas somehow converge is that life has evolved in conjunction with the rest of the Universe. We are an embodiment of the same laws that have shaped the Universe and our imagination is intimately correlated to it. Consciously or subconsciously we find that we converge towards these laws. In this view the driver of this convergence, unlike in previous points, is not any limitation on our part to describe the Universe but rather a natural attraction towards the laws that bind it. These views may seem pretty similar, but the main difference is that the latter is more optimistic. Rather than us creating our reality and then only being able to describe the Universe through this reality, it essentially gives us hope that, as we embody the laws describing the Universe we are already on the right track. But will simplicity lie at the end of this journey?

One of the notions that scientists hold in highest esteem is Occam's razor. William of Occam, a fourteenth-century English logician and Franciscan friar, tells us that assumptions should not be multiplied without necessity, or in other words, the simplest explanation is usually best. While

you could argue that simplicity is entirely subjective, in Chapter 10 I will show that there is an objective view of simplicity that is universal.

Taking Occam's logic to the extreme would also mean reducing all the explanation about everything in the Universe to a single all-encompassing principle. Imagine how easy this would make our lives; falling in love, the motion of planets, the movements of the stock market, all being explained through this one principle.

But is this really taking Occam to the extreme? Why not try to even get rid of this one principle and deduce everything without any principles? This surely is simpler still and therefore, in line with Occam's logic, must be a better reflection of reality? Deduction without any principles is what the famous American physicist John Wheeler called a 'law without law'. He reasoned that if we can explain laws of physics without invoking any a priori laws of physics, then we would be in a good position to explain everything. It is this view that is the common scientific take on 'creation out of nothing', *creation ex nihilo*.

Gottfried Wilhelm Leibniz, the famous German mathematician and philosopher and one of the inventors of the mathematical technique of calculus, used this logic in his proof of the existence of God. He found it surprising that something, rather than nothing, exists in the Universe, given that nothing is by far the simpler state. The only reason he could find for something to exist at all is that an independent being created that something. This for him was enough evidence to suggest an external influencer—the influencer being God. So even he, like many others, could find no better answer to the *creation ex nihilo* question than postulating a supernatural being.

The trickiness of having a law that explains everything without postulating a law (or some kind of general principle) in the first place was nicely addressed by one of Wheeler's students, Oxford physicist David Deutsch. On this issue Deutsch reasons as follows: 'If there were no all-explanatory physical principle P approachable by the methods of science, this would presumably mean that there exist aspects of the

natural world that are fundamentally inaccessible to science.' In other words, if we cannot find an overarching principle, then science cannot explain the Universe and fails in its ultimate objective. Deutsch reasons that any inability to explain the Universe through a single principle *P* would run directly counter to rationalism and 'to our view of physics as the universal science, which has hitherto been the driving force behind progress in the subject and which we should be extremely reluctant to abandon'.

However, as Deutsch points out, the flip-side of this is also problematic. If there were such an all-explanatory principle *P* within physics, its origin would be forever insoluble, given that no principle (or law) can explain its own origin or form. It's like asking an air-conditioner 'why are you an air-conditioner and not a chair?'. Clearly the answer lies outside of the air-conditioner, because the air-conditioner itself was just made that way. So, paradoxically, *P*, the ultimate principle of physics or the law that explains everything, just cannot be. Again its origin must lie outside of physics and hence Wheeler's seemingly self-contradictory expression 'law without law'.

Deutsch's logic shows the fine line we have to walk if we are to try to explain the whole Universe from one single principle. But what exactly is it that this principle is trying to explain? Are we talking about explaining all objects in the Universe, such as chairs and air-conditioners; are we trying to explain social interactions such as falling in love; or are we talking about something more fundamental, like the basic building blocks of matter and their interactions? Surely we need to explain all of this, the origin of all the stuff in the Universe and how it's tied together.

This book will argue that information (and not matter or energy or love) is the building block on which everything is constructed. Information is far more fundamental than matter or energy because it can be successfully applied to both macroscopic interactions, such as economic and social phenomena, and, as I will argue, information can also be used to explain the origin and behaviour of microscopic interactions such as energy and matter.

As pointed out by Deutsch and Wheeler, however, whatever candidate is proposed for the fundamental building block of the Universe, it still needs to explain its 'own' ultimate origin too. In other words, the question of everything from nothing, *creation ex nihilo*, is key. So if, as I claim, information is this common thread, the question of *creation ex nihilo* reduces to explaining how some information arises out of no information. Not only will I show how this is possible, I will also argue that information, in contrast to matter and energy, is the *only* concept that we currently have that can explain its own origin.

So does information also help us find the all-explanatory principle, *P*, discussed by Deutsch? I argue in the third part of this book that when viewing reality in terms of information, this question no longer even makes any sense. We find that the journey itself, in this case the method with which useful information arises, becomes more important than the ultimate destination (the concept of an explanatory physical law). Indeed we question whether there is any ultimate destination at all, or whether, as the Universe evolves, then so does our target, firmly placing the concept of an ultimate physical principle only in our created reality rather than as a necessary construct for the Universe itself.

So what is the important question that we must address? If we agree on information as a natural framework within which to understand our reality, then we should be able to explain all natural phenomena in terms of it. This is the subject of the core of this book, Chapters 3–10. As we go through the chapters, we will see that it is actually the decrease of information that equates to a better understanding of it. Though this might sound odd initially, intuitively we know this to be true—in that when we understand something better we find that we can summarize it within a few basic principles. For example, instead of having 100 different laws to describe the dynamics of a tennis ball being thrown into the air, each law applicable under a different set of conditions, having one law capturing any possible condition is something that we feel gives us a much better understanding. Hence we

equate a better understanding of our reality with a compression of the amount of information that it contains.

Conversely, whilst we work tirelessly to reduce the amount of information in our reality, there is a fundamental argument that suggests that the amount of information in the Universe as a whole, if understood correctly, can only ever increase. This is the subject of Chapter 5. This implies that as the Universe reveals more and more to us, our reality of what is and isn't possible consequently grows, leading to more information that then needs to be compressed. The analogy that I often like to give is of a donkey with a carrot hanging at a fixed distance in front of it. As the donkey moves closer to the carrot, thinking he's almost made it, the carrot moves in line with the donkey. The donkey, not realizing that the carrot is attached to it via a stick, continues to try and try, unaware that he is ultimately doomed to failure (it is a donkey after all). While he covers a lot of distance (and gets to know the structure of the carrot intimately), the donkey ultimately fails in his primary objective.

In this sense there is a dichotomy between our desire to compress information (distil our whole understanding of reality into a few encompassing principles) and the natural increase of information in the Universe (the total amount we need to understand). This desire to compress information and the natural increase of information in the Universe may initially seem like independent processes, but as we will explore in much more detail later there may be a connection. As we compress and find all-encompassing principles describing our reality, it is these principles that then indicate how much more information there is in our Universe to find. In the same way that Feuerbach states that 'Man first creates God, and then God creates Man', we can say that we compress information into laws from which we construct our reality, and this reality then tells us how to further compress information.

While some may disagree, I believe this view of reality being defined through information compression is closer to the spirit of science as well as its practice (the so-called scientific method to be discussed in great detail in Chapters

10 and 12). It is also closer to the scientific meaning of information in that information reflects the degree of uncertainty in our knowledge of a system, as will be shown in Chapter 3.

Perhaps the view of the Universe that will be promoted here should more appropriately be called 'annihilation of everything' as opposed to 'creation out of nothing', as ultimately it is compression that we argue defines reality. This will be explained in more detail in Part Three of the book.

Key points

- We present the notion of our reality, which is our understanding of the Universe and what is and is not possible within it. Our notion of reality continually evolves with our progress.
- We wrestle with the challenge of whether there could be an ultimate law that describes the Universe and the question of how this could arise out of nothingness, *creation ex nihilo*.
- This book will argue that information is the underlying thread that connects all phenomena we see around us as well as explaining their origin. Our reality is ultimately made up of information.

2
Information for all Seasons

Imagine that you arrive late at a party. Everyone is already there, sitting at a big round table. The host invites you to sit down with the others and you realize that they are engaged in what appears to be some kind of a game. The host tells you nothing other than to sit down and join in. Let's say that you quite like playing poker, and you get excited at the prospect of participating, but you quickly realize that this is not poker. Then it dawns on you that you actually have absolutely no idea what is going on. You turn around to consult the host, but he seems to have disappeared. You take a deep breath and keep quiet, not wanting to reveal your ignorance quite so early in the evening, and you quietly continue to observe.

The first thing you notice is that no one is allowed to utter any words, so it's not obvious at all whether this is a game. This seems slightly odd but you think this may be one of the rules of the game and so you play along. You observe that the players are using a common deck of cards, resembling Tarot cards, each card with an elaborate picture on it, such as a warrior killing a lion, or a lady holding two crossed swords. After a while it becomes clear that players take turns to reveal a set of cards, one at a time. As each subsequent card is laid down, adjacent to the previous one, the other players closely observe the card being laid down as well as any body language of the player to further substantiate the meaning of the card.

So it's finally the turn of the player sitting next to you. He puts down a king standing over a dead lion with his sword raised above his head; you think to yourself, 'Is this guy talking about a particular king who killed a lion?', 'Is he talking about royalty in general?', or 'Is this card a metaphor for some kind of personal triumph?'. As you develop your thoughts on this, the next card is placed, which is a red dragon. You think initially that this is some kind of metaphor for danger, but when you look at both cards together, you

reason that maybe they represent a Welsh king (the red dragon is the national icon of Wales) or perhaps a powerful person facing danger. The next three cards shown are: two crossed blades, a river, and finally a beggar.

By now it's obvious that they are all trying to convey some kind of message to each other through these cards and their body language. And it's also clear that you probably cannot work out the meaning of this game until you have seen a sufficient number of cards. But you start to ask yourself, what exactly are they trying to convey—what is the main point of this activity? Are they telling their life story, making up a story for each other's entertainment, or perhaps is each combination of cards worth a certain number of 'points'? If it is a game, how do you win it, and if it's not a game, what is the point of it?

A story of this type was imagined by a well-known Italian fiction writer Italo Calvino. The point of his story was that every player is trying to tell others about their life, but only using the images on the cards with a little bit of creative gesticulation and grimacing on the side.

In his book Calvino used this card game as the main metaphor for life. The question is why? Well, it is difficult for me to guess what the writer really wanted to say. Writers are artists, and frequently the point of their work lies precisely in the fact that they are ambiguous and that different people will interpret the same work of art in many different ways. But I am a scientist (as were, incidentally, Calvino's parents) and I'd like to tell you that what Calvino's card game represents is not all that different from how we generate our understanding of reality.

Calvino's card game is like our dialogue with Nature, in other words, the rest of the Universe. Each of the players at the table represents different aspects of Nature and you are the observer. For example, one player could be economics, one player could be physics, one could be biology, and one could be sociology. Each of the players in turn reveals a little more about their own rules and behaviour as time goes on. Nature, like the players, is silent but reveals its intention through events and the surrounding environment. Unsurprisingly, the

language Nature uses to communicate is 'information'. The card game indicates that information comes in discrete units, one card at a time. We cannot divide this card into smaller units. The first message of Calvino's metaphor is therefore that there are basic atoms of information that are universally used. In science, we call these atoms 'bits' or binary digits. We will discuss these 'bits' more precisely in Chapter 3.

The second message of Calvino's story is that any sequence of cards, no matter how transparent its message may seem, has still to be interpreted by the observer (in this case you and the other players). The interpretation may, or may not, be true to what the player intended to convey and may vary widely between different observers, and furthermore the observer himself may have several different views of what he has observed. This is synonymous with the inherent uncertainty we find when we observe Nature and two people may have radically different interpretations.

Interestingly, when it is your turn to play, you become the player and Nature becomes the observer. As you lay down your cards, this reflects back on Nature; there is a duality here—you cannot be at the table without affecting the game. This is the third message of Calvino's story, that in real life you are simultaneously the observer as well as being the player.

The fourth message we can draw from Calvino is that the same card can also mean different things based on which other cards it is drawn with. Regardless of who observes it, each card has its own inherent degree of uncertainty, the same red dragon card can mean danger, fear, or represent the country of Wales, depending on the other cards in the set. Once the whole set of cards is presented, the meaning of each card within this context becomes clearer. Therefore relating Calvino's second and fourth points, these cards, as well as representing bits, depend on who interprets them, as well as the other cards they are drawn with. In this sense, we cannot look at any card individually—they must be considered within the context of the sequence of cards they are drawn with. It's no surprise that this property, in science, goes under the general name of 'contextuality'.

One of the most striking conclusions that follows from this contextuality is that we can never be sure about our interpretation of Nature, given that the next bit of information could falsify our previous view and completely change the essence of the message. In science for example, we could see 1000 experimental results confirming a particular theory, but one subsequent result could completely falsify it and indicate that we have utterly misunderstood the message that Nature is conveying. In Calvino's story, this similarly means that you cannot be sure of the message until the last card in placed on the line. The last card may change the whole point of the story. This is very reminiscent of the Ancient Greek philosopher Socrates' statement that 'no one should be considered happy until they are dead'. You may be happy for most of your life, but until your last breath you can never be sure that you have had a happy life. We will see that the whole edifice of scientific knowledge also rests on this kind of (somewhat brutal) logic.

Analysing Calvino's game a little more also draws some interesting parallels with our observation of Nature. Like the observer in the story, we humans also arrived late to the game. Taking the game as a metaphor for life, if the game has been progressing for 10 years, we only just arrived a couple of minutes ago. Some elements of Nature, such as physics, have been there since the very beginning. So, a huge amount of information has already been conveyed that we haven't yet taken into account as we generate our model of reality.

Calvino takes the players as granted. The scene is already set but Calvino does not tell us why the game started and who invited the players. He leaves this question open, just as it is open in reality. This raises the same issue of where the players come from, and reduces to the challenge of *creation ex nihilo*.

Of course, there is much more to interpreting reality than can be portrayed in any story like Calvino's. It does not give us any concrete details or prescriptions of how exactly we should quantify information and apply it to any given situation, let alone the whole Universe. For example, the arrangement of Tarot cards does not lead us to infer a unique story. How do we decide which story is then more likely than

others? Or should we maybe not choose a single story, but combine all the stories into some kind of super-story?

Another crucial aspect missing in Calvino's story, if we use it as an analogue of how Nature presents us with information, is to do with the fact that in Calvino's story, once each card is laid, it cannot be changed. Each card has a definite state (its picture) and, whilst this state may be interpreted differently, it cannot change once it has been laid down. For example, a card showing a red dragon cannot 'magically' change to another card as soon as the next card is drawn, or as soon as it has been observed by someone. As counterintuitive as it may sound, the omission of this interaction between cards, and also between the cards and the players, will be seen to be crucial as we discuss our best physical description of reality, quantum theory, in Part Two of the book.

The reader probably comes to this book with a vague idea of what information is. In everyday parlance information is frequently synonymous with knowledge. We believe we know something when we can talk about it at sufficient length and breadth without being contradicted by any of our listeners. However, although this is the common meaning of the word 'knowledgeable', it is not what a scientist would consider to be knowledge. To a scientist, any knowledge always refers to the knowledge of the future. Hence historians are not scientists—historians make predictions about the past—but science is all about predictions concerning the future. Neils Bohr, one of the grandfathers of quantum theory, jokingly said on this issue that 'It is difficult making predictions, especially about the future'.

Guessing what will happen, means that there is always some risk involved. When we are trying to predict the future, we invariably need to make some leaps of imagination, either because the future is intrinsically uncertain or because we do not have enough information about it. This uncertainty was already explored by Calvino, in that we cannot be sure of the message until the last card is placed on the table. The last card may change the whole point of the story. Unlike in Calvino's story, in which there is a finite set of cards, Nature seemingly lays down cards indefinitely. Unfortunately this means that

we have to guess the message that Nature is trying to convey as more and more cards become apparent. As a result, we may be proven wrong by a later card, but this is just a necessary risk inherent in how science works.

Typically, a physicist, when studying an atom say, calculates its properties using pen and paper, or more often these days with the aid of a computer. Then, he goes into the laboratory and makes measurements (these days it is typical for those who calculate and those who measure to be different people, but this need not be so). Finally, the physicist compares measurements with his theory, and if the two coincide to sufficient accuracy he is satisfied that his understanding of the phenomenon is good. If the experiment contradicts the theory—and he is certain that there are no crucial experimental errors involved—then the theory, i.e. our interpretation of the message Nature is trying to convey, must be changed.

This is the basis of the scientific method that has helped us understand various aspects of Nature within a short span of 400 years. It is also this same method that can probably be considered one of the defining features of modern civilization.

Whilst we have thus far been driven by the question of why there is information in the Universe and how it is communicated to us by Nature, our ultimate intention is to show how information describes the reality that we observe. We will do this by following Roger Bacon's dictum of 'analysis and synthesis' and first analyse each of the pillars of reality individually before we synthesize this into an overall unified picture.

Each of the pillars of our reality (players in Calvino's story) will be analysed in terms of how they embody and convey information. While I will be presenting a message from each of these pillars in my own information-centric way, these messages are all well established in the scientific community. The reader may not agree with my ultimate view of encoding reality, but hopefully he or she will find the discussion of the separate pillars valuable in themselves.

The main pillars that we will discuss are:

- **Chapter 4—Player 1: Biology.** The first major application of information was in biology where genetics developed entirely using the language of information preservation and transmission. Here information is easiest to understand and has a clear and well-defined meaning. Biological information is famed for its endurance, but the underlying principles are in fact universal. We can use them to offer a new framework for running a successful business.

- **Chapter 5—Player 2: Thermodynamics.** Physics and information have had a long-standing relationship and I use this to talk about the infamous Second Law of thermodynamics. It states that the tendency of the Universe is to decay into chaos. I explain how this is to be understood in terms of information and why it does not contradict the biological preservation of information. Here I will also use information to present novel insights into the topics of global warming, environmentalism, and offer a new perspective on how to plan your diet.

- **Chapter 6—Player 3: Economics.** Having convinced you that biology and physics are all about information, I now claim that human behaviour too is based on the same information-theoretic principles. In particular, betting on random processes, such as in a casino or the stock market, is maximized when we follow these principles. Here we will see how to invest successfully by using laws of information.

- **Chapter 7—Player 4: Sociology.** More complex social structures, such as the distribution of cities, the wealth of citizens, and the social order are also seen through the eyes of an information theorist. This chapter is the culmination of the first part of the book, unifying a number of disparate phenomena through one and the same logic. Here I will discuss how to improve your social standing and how racial segregation can occur even within the most ardent group of xenophiles.

- **Chapter 8—Player 5: Quantum Physics.** In the second part of the book, I explain that the information in the real world is of a different kind from what it appears to be at

first sight. Though still quantified in terms of bits, information is actually far more powerful than what we thought possible. This is because the world is ultimately quantum mechanical. This chapter explains the basics of quantum information which has some bizarre and rather radical features. We will see how to communicate so securely that even the CIA has no chance of eavesdropping on our conversations.

- **Chapter 9—Player 6: Computer Science.** This new form of information, based on quantum theory, can be used to compute faster than anything we have seen so far with our PCs (which are in the commonly accepted language of classical computers). Here I explain how hacking into your bank account will only take a few seconds with a quantum computer and how biological systems may already be capable of some simple forms of quantum computation.

- **Chapter 10—Player 7: Philosophy.** If the Universe has quantum information at its core—which is what I start to argue here—then we revisit the age-old problem of determinism versus free will. Can we act out of our own accord, or are all our actions predetermined? Here I will try to convince you that randomness and determinism do not oppose each other. I present an example of where they work hand in hand to teleport objects across the Universe.

Of course, some purists might argue that there is really only one player in Nature, and that player is physics itself. From the cards that physics reveals, the hands of all the other players follow. However, in this book I am arguing that it is the cards that are the most fundamental part of this game. Hence each of the players should be treated equally even though there may be some repetition in their messages, e.g. some of what economics reveals to us about human nature has already been captured by biology.

Once we conclude our analysis we then begin to synthesize these messages in **Chapters 11 and 12**. The result of this synthesis will be a reality, encoded through bits of information. Here we will view the Universe as a big quantum computer, running the biggest possible computer game to

generate our reality. The programmers are the players in Calvino's card game and their software summarizes everything they've learnt from playing the game. Using the same logic, we can calculate the amount of information that can be stored inside any object, even the human brain.

Part Three of the book will also argue that information is the only appropriate entity on which to base the ultimate theory of everything. Not only does information present a framework in which gravity can be seen as a mere consequence of quantum theory (integrating quantum theory and gravity is the greatest challenge of modern physics), but it suggests how information can give rise to the 'law without law' and thereby cut the Gordian knot of *creation ex nihilo*.

Some aspects presented in the final chapters will be speculative or still under discussion in the scientific community, and I will warn the reader when this is the case. However, whilst some of these aspects may turn out to be wrong, I hope that the reader will enjoy the intellectual journey. On this let me finish by quoting the famous eleventh-century Persian poet and astronomer, Omar Khayyam:

> Those who conquered all science and letters,
> And shone as beacons among their betters,
> Did not find the thread of this Tangled Heap,
> Only told a story, then they fell asleep.

Key points

- Calvino's card game forms an effective metaphor for the way that we observe and understand reality.
- Information is the language Nature uses to convey its messages and this information comes in discrete units. We use these units to construct our reality.
- The main players in Calvino's card game represent different aspects of Nature. I have chosen these players to be biology, thermodynamics, economics, sociology, quantum physics, computer science and philosophy.

- Key messages from each of these players will be analysed in an information-centric manner in the chapters to come.
- Synthesis of the key messages from each player will result in our view of how reality is generated or encoded.