INTRODUCTION: INFORMATION IS WHAT INFORMATION DOES

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1 INTRODUCTION: WHY THIS HANDBOOK?

Information is a high-frequency and low-content phrase that permeates our ordinary language without attracting much attention, since its meaning has long eroded. Even so, is there more to the notion, and in particular, is there philosophy to it? The editors of the series of 'Handbook of the Philosophy of Science" thought so, when they invited us to contribute a volume, more years ago than we care to remember. But right at the start, a distinction must be made concerning the aim of this text, which comes from the philosophy of language. A Handbook for an established field has a descriptive function in terms of 'what there is', serving as a record of insights and issues. But other, activist Handbooks have a *performative* use, trying to create a new field by a 'let it be'. The present volume is definitely of the second category.

Clearly, one cannot just create an academic discipline by fiat when there is no material to go on. But as it happens, information is a unifying notion across the sciences and humanities, with a backbone of serious mathematical theory. Moreover, there is even a whole discipline of 'informatics' ('computer science', in the unfortunate terminology used in some countries) which studies the structure of representation and transformation of information by machines, but gradually also by humans, and various hybrids of the two. Indeed, universities in several countries have created schools of Informatics or Information Sciences, highlighting the central role of information and its associated themes of computation and cognition in the modern academic landscape.

But this observation again calls for a distinction, this time concerning our purpose. 'Philosophy of information' might mean philosophy of the information sciences, just as there is philosophy of the natural sciences, the life sciences, or humanities. Such methodological reflection on specific fields is absolutely necessary given the explosion of relevant technical research. It will be found in abundance in the pages of this Handbook, with authors engaging in foundational analysis of disciplines such as computer science, economics, linguistics, or physics. But there is also the parallel, and in some ways more ambitious aim of information as a major category of thought within philosophy itself, which might have the potential of transforming that whole field. Indeed, major philosophers like Fred

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Dretske or John Perry have argued that perennial questions of epistemology and other core areas of their field can be solved, or at least taken much further, from an information-oriented stance. Beyond that largely analytical tradition, in recent years, Luciano Floridi has been arguing forcefully that a well-conceived philosophy of information might affect the field as a whole, making distinctions like 'analytical' vs. 'continental' irrelevant.

We are sympathetic to both purposes: foundations of the information sciences and transformation of core philosophy, even though the second seems more programmatic than the first right now. In what follows we will discuss some more concrete themes in this Handbook, and then return to these broad purposes.

2 A VERY BRIEF HISTORY OF INFORMATION

Philosophy

The term information is of Latin origin, and authors like Cicero and Augustine used it in the context of Plato's theory of ideas (or forms) and its successors. In particular, Cicero uses 'in-formare' to render the Epicurean notion of 'prolepsis', i.e., a representation implanted in the mind [Capurro and Hjørland, 2003]. In the Middle Ages, a significant shift occurred. In the 15^{th} century, the French word 'information' emerges in colloquial language with a cluster of meanings: 'investigation', 'education', 'the act of informing or communicating knowledge' and 'intelligence'. The technical term 'information' then vanishes from philosophical discourse as though it had lost its appeal. Instead, when the English empiricists went back to the original Platonic inspiration, they coined the term 'idea' (derived from Platonic 'eidos'): "whatsoever is the object of understanding when a man thinks … whatever is meant by phantasm, notion, species, or whatever it is which the mind can be employed about when thinking" [Locke, 1961, Essay I,i,8]. The philosophical adventures of this notion of 'idea' run from Hume, Kant, and the German idealists up to Husserl and beyond. But like famous Cats through history, 'information' has had many more lives than just one — and to these, we now turn.

Coding

Information has long been associated with language and *coding*. Like theoretical philosophy, the practical ambition to hide information in messages and to then decode these messages with, or without a key dates back to Antiquity [Kahn, 1967]. Cicero's contemporary Julius Caesar used code systems to communicate with his generals, and so did his Hellenistic and Chinese predecessors — and code breaking must be equally old. Reflection on this practice soon followed. The efficiency of assigning shortest codes to most frequent signals has long been known, witness the 10^{th} century Arabic texts on cyphers and decoding via frequencies mentioned in Singh [1999]. With the invention of book-printing in the 15^{th} century, typesetters soon discovered that they needed more es than zs in a font. Characteristic frequencies of letters in languages were used to decode simple replacement ciphers.

The 18th century saw the emergence of ‘black-rooms’ in Europe with the task of encoding and decoding messages for political purposes. With the development of the first electronic communication media, efficient coding systems became of wider use. In 1838, Samuel Morse designed his telegraph code on the basis of a statistical analysis of a Philadelphia newspaper.

Physics

Another step toward the modern concept of information occurred in 19^{th} century physics. When explaining macroscopic events in terms of large quantities of discontinuous microscopic ones, Rudolf Clausius [1850] introduced the statistical notion of *entropy*. Entropy measures the number of different microscopic states a macroscopic system can be in. The entropy in a container is higher if the particles are evenly distributed over the space in the container. With this concept, Clausius formulated what we now call the Second Law of Thermodynamics: a closed system either remains the same or becomes more disordered over time, i.e., its entropy can only increase. The philosopher Henri Bergson once called this “the most metaphysical law of nature” [Bergson, 1998]. Clausius’ famous paper ends with a disturbing observation from an informational point of view: “The energy of the universe is constant — the entropy of the universe tends toward a maximum.”

Mathematics

In the 20^{th} century, ‘information’ became a subject for mathematical theory, with the pioneering work of Ronald Fisher on the foundations of statistics [Fisher, 1925]. Indeed all of probability theory might be seen with some justice as a form of information theory, with objective probability closer to physical perspectives, and subjective probability closer to information as used by rational human agents. While this is true, we have decided to concentrate on more specific ‘information theories’ as such. The pioneering example is the work of Claude Shannon on channel transmission [Shannon, 1948], which may well be most people’s association with ‘information theory’. Shannon defined the amount of information in a message as the negative base-2 logarithm of the probability of its occurrence from a given source over a given channel — thus measuring in ‘bits’, which has become a household term.

Actually, this notion fits with the physics tradition via one transformation. The total entropy of two independent systems is the sum of their individual entropies, while the total probability is the product of the individual probabilities. Already Ludwig Boltzmann proposed to make the entropy of a system proportional to the logarithm of the number of microstates it can be in. Shannon’s quantitative approach is a momentous shift away from the common-sense conception of meaningful information, but it has been spectacularly successful, witness its use in many chapters of this Handbook.

Computer science

Even so, Shannon's is not the only quantitative version of information to appear in the 20^{th} century. In the 1960s, Kolmogorov, Solomonoff and Chaitin [Solomonoff, 1997; Chaitin, 1987; Li and Vitányi, 1997] developed a new information measure in terms of optimal coding by a computational device. The information in a string X is now an absolute number, viz. the length of the shortest code of a program that would lead a universal Turing Machine to output string X. It can be shown that this definition makes sense independently from accidental features of code language and computing device. Now, highly regular strings will have low complexity, while highly random strings have high complexity. Thus the information content of a string 'reverses' in an obvious way. Kolmogorov complexity is a major tool in computer science (the most authoritative source is Li and Vitányi [1997]), with foundational uses in complexity theory and learning theory.

Again, there are strong links here with the earlier traditions. For instance, strings with low Kolmogorov complexity have low entropy, random strings have high entropy. As we shall see in several chapters of this Handbook, the kinship between thermodynamics and mathematical and computational information theories ensures an almost seamless translation of concepts and applications.[1]

Logic and linguistics

So far, our historical tour of information has taken us from abstract philosophy to hardcore quantitative science and computation. But the 20^{th} century also produced another strand of technical information theories, which will be very much in evidence in this Handbook. For a start, our human information is most obviously expressed in natural language, and indeed, analyzing even the simplest episode of language use quickly reveals a host of subtle informational phenomena. What is a speaker trying to convey, on the basis of what knowledge about the hearer's information? Figuring out this communication-oriented sense of information — which Shannon acknowledged explicitly as significant, but then ignored — involves a study of semantic meaning, knowledge, and other notions that form the domain of linguistics, philosophy, and logic. Modern logical modeling of information dates back to the 1930s with Alfred Tarski's fundamental work on the concept of truth (cf. [Tarski, 1944]). Of course, traditionally, logic already studied informational processes like inference, which work largely on linguistic code, without an explicit model of reality attached. Logical accounts of information tend to be qualitative, in terms of sets and orderings rather than numbers, but they are just as rigorous as quantitative accounts. The chapter by van Benthem & Martinez in this Handbook is a broad survey of sources and varieties. Finally, logic-based accounts of information, too, have strong connections with the foundations of mathematics

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[1] In a slogan, information theory is the thermodynamics of code strings, while thermodynamics is the information theory of particles in space. Some authors take this analogy to extremes, viewing black holes and even the universe as a computational system [Lloyd and Ng, 2004].

and computer science, and so we have another major kind of 'information theories' that goes into the total picture of this Handbook.

Broader uses in society

A history of the emergence of 'information' as a staple of public discourse in the 20th century is yet to be written. It appears to be connected with modern intelligence services and communication technologies like the telegraph, and later, the computer. At the end of the 19th century, several countries started systematic collection of military information. The US Office of Naval Intelligence was established in 1882, followed by a Military Information Division — with one clerk and one officer — in 1885. Its task was to collect "military data on our own and foreign services which would be available for the use of the War Department and the Army at large." A modern use of the term information in this context can be found in the *'World Fact Book'*, an annual publication of the CIA:

> *Information is raw data from any source, data that may be fragmentary, contradictory, unreliable, ambiguous, deceptive, or wrong. Intelligence is information that has been collected, integrated, evaluated, analyzed, and interpreted.*[2]

In this compact passage, various broad themes running across this whole Handbook occur in a nutshell, viz. 'information as the act of informing', 'information as the result of the act of informing', and 'information as something that is contained in the message used to inform'. In addition to the impact of this military usage, much broader reflection on information has been generated by recent technologies like the Internet, again related to issues in this Handbook in interesting ways. Just as in 17^{th} century physics, what we see is an intriguing parallelism, and indeed a lively stream of interaction, between scientific, technological and social developments [Castells, 1996; Kahn, 1967; Capurro and Hjørland, 2003].

Philosophy once more

While scientific and social developments made information a crucial notion, little of this penetrated into modern philosophy. Although Gödel's incompleteness results, the Church-Turing thesis, and Turing's ideas on machine intelligence generated much philosophical debate, this did not lead to widespread philosophical reflection on the notion of 'information' itself. To be sure, there were some serious philosophical responses to Shannon's theory around 1950, witness Bar-Hillel and Carnap [1953], which took a closer look at the interplay of what they saw as equally viable quantitative and logical notions of information, starting off a tradition in 'confirmation theory' continued by Jaakko Hintikka, and many others.[3]

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[2] `https://www.cia.gov/library/publications/the-world-factbook/docs/history.html`

[3] Cf. [Hintikka, 1973; Kuipers, 2000]. Our companion publication "Handbook of the General Philosophy of Science" presents the current state of the art in confirmation theories.

Solomonoff, who is one of the founding fathers of algorithmic information theory, and whose work was partly motivated by philosophical questions concerning the nature of probability and the induction problem, studied with Carnap in the fifties. Until now this work never percolated to mainstream philosophy. 'Information' is not mentioned, for instance, in the well-known history of logic [Kneale and Kneale, 1962], nor does it have a lemma in Paul Edwards *"Encyclopedia of Philosophy"* of 1967. Things started changing around 1980. Fred Dretske gave information theory its due in epistemology [Dretske, 1981], and the same is true for the work of Jon Barwise and John Perry in the philosophy of language [Barwise and Perry, 1983]. On the latter view, triggered by ideas from cognitive 'ecological psychology', logic should study the information flow in rich distributed environments with physical and human components. All these philosophers use the notion of information to throw new light on classical issues of knowledge, objectivity, representation and 'aboutness', thus facilitating 'second opinions' and new solutions. Finally, we already mentioned Luciano Floridi's seminal work on a new 'Philosophy of Information' at the start of the 21^{st} century [Floridi, 2003A; 2003B].

Modern interdisciplinary trends

This historical sketch provides the background for the main themes that the reader will find in this Handbook. But maybe we should also explain our cast of authors, which mixes philosophers with practitioners of other disciplines. This combination is well in line with what has happened over the last two decades in foundational studies of information, with topics moving in and out of philosophy. Indeed, Barwise and Perry already started the interdisciplinary *'Center for the Study of Language and Information'* (*CSLI*) at Stanford, a hot-bed of encounters between philosophers, linguists, computer scientists, mathematicians, and psychologists. Its current director Keith Devlin is one of our Handbook authors.

At the same time, in Europe, natural language semantics took an informational turn. Jeroen Groenendijk and Martin Stokhof[4] introduced information of language users in defining meanings of key linguistic constructions, including speech acts like questions. With Peter van Emde Boas, a pioneer in the study of parallels between natural and programming languages, and Frank Veltman, who had developed an update semantics for conditional expressions, they redefined meaning as 'potential for information update' based on abstract computation in appropriate state spaces. Similar ideas underlie the influential discourse representation theory of Irene Heim and Hans Kamp. Details on this linguistic paradigm shift may be found in the chapter by Kamp and Stokhof in this volume. By 1986, this led to the foundation of the 'Institute for Language, Logic and Information' in Amsterdam, better known today as the *ILLC*, the *Institute for Logic, Language, and Computation.* Similar initiatives include the European Association for Logic, Language and Information, and its annual *ESSLLI* Summer Schools, as well as its international off-spring in other continents.

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[4] Editors of the companion volume *Handbook of the Philosophy of Language* in our series.

One more major interdisciplinary strand in the 1980s was the rise of *epistemic logic* describing agents' knowledge 'to the best of their information'. Epistemic logic was first proposed by Jaakko Hintikka [Hintikka, 1962] as a tool for philosophers, and taken further by David Lewis [Lewis, 1969] and Robert Stalnaker [Stalnaker, 1984]. Epistemic logic was invented independently by Robert Aumann in economics in the 1970s, in his eventually Nobel-Prize winning analysis of the foundations of Nash equilibrium through common knowledge of rationality. Since the 1980s, when Joe Halpern and colleagues at *IBM* San Jose started the still-thriving *TARK* conferences on *'Reasoning about Knowledge and Rationality',* while themselves making major contributions to the study of information and communication, the field has lived at the interface of computer science, philosophy, and economics.[5]

In the 1990s, a further notable new force was the rise of 'Informatics': a new academic conglomerate of disciplines sharing a natural interest in information and computation as themes cutting through old boundaries between humanities, social, and natural sciences. By now, there are Informatics schools and institutes in Bloomington, Edinburgh, and Kanazawa, to name a few, and the founding dean of such a School at Indiana University, Mike Dunn, is one of our Handbook authors.[6]

While all this organizational and social information may grate on ears of traditional philosophers (how far away can the Mammon be?) — to us, it seems highly relevant if Philosophy of Information is to have a significant future as a vibrant endeavour with many sources.

3 INFORMATION THEORIES, THREE MAJOR STRANDS

We have sketched a rich history of information studies ranging through the whole academic spectrum into society. The reverse side of this wealth is the diversity. What do all these themes and fields, worth-while as they may be *per se*, have in common, except at best a metaphor? This impression of diversity may even be reinforced when the reader gets to our actual chapters. Before sketching their content, then, let us first draw a few lines confronting some doubts and worries.

Just a metaphor?

'Information' may be a ubiquitous phrase, and even a real phenomenon, and yet it might be just a metaphor leading to vague philosophy, like 'system' or 'game' have done in the past. The real situation seems less bleak, however. As with terms like 'energy' or 'money', there is indeed a general usage of information where little can be said beyond generalities. Energy is what drives inanimate processes and animate activities, and what allows us to relate the effort involved. Money is

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[5] Epistemic logic as information theory is a new view, proposed in [van Benthem, 2006], and the chapter by van Benthem and Martinez on 'Logic and Information' in this Handbook.

[6] Dunn's chapter in this Handbook provides much additional detail beyond our historical sketch, while also mapping out connections to major approaches to information in the foundations of logic and computer science.

what makes transactions possible without undue real transportation of goods. In both cases, general usage is backed up by pockets of precise use in expert circles, grounded in mathematical theory: thermodynamics, or economics. This interplay causes no real problems: we understand the broad usage, and we specialize and make it more precise as needed. These lessons transfer to information.[7] Indeed, when Keith Devlin says tongue-in-cheek to broad audiences that "information is the tennis ball of communication", he actually formulates a very similar role for information as for money, viz. as the abstract currency that gets transferred when people say or observe things. And he also gets the idea right that information usually arises in complex multi-agent settings, where interaction is of the essence. But on that topic, we will have more to say below.

Go for a larger family of notions?

Can information stand on its own in conceptual analysis? Compare the case of *knowledge*. Most standard philosophical analyses, mainstream like Plato's, or more avant-garde like Dretske [1981] or Nozick [1978], make it part of a larger cluster of notions, involving also *truth, belief, information (...)*, and perhaps even *counterfactuals*. We are usually not after single concepts in philosophical analysis: we are also charting their closest relatives and friends. This is an issue on which we have not arrived at a final position. Natural candidates for a clan of related concepts — not identical, but naturally intertwined — in our case would be: *information, probability, complexity, meaning, coding,* and *computation*. Our Handbook does not really take a stand here. While using information as its running theme, it does give extensive coverage to many of these related notions.

Three major concepts of information

One might assume a priori that there is just one notion of information. But one striking feature, even in our brief history, is the existence of respectable, but very different mathematical views of what makes it tick! We have seen approaches, roughly, from logic, physics, and computer science. Should we first assure ourselves that these all amount to the same thing? Perhaps not. The plurality of mathematical theories of information may reflect a genuine diversity in the concept itself, which needs to be frankly acknowledged.

Compare the case of probability, another crucial foundational notion across the sciences whose precise nature has been under debate ever since its rise in the 17^{th} century. Carnap 1950 proposed a famous conceptual dichotomy between two irreducible, complementary notions: *Probability-1* for objective frequency, and *Probability-2* for subjective chance, and this is still widely seen as a major duality

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[7] That 'money' leads the way need not be a bad thing, if we recall Karl Marx' famous saying that 'Logic is the Currency of the Mind'. A mere slogan perhaps: but, how rich and suggestive!

between two different legitimate concepts in both mathematics and philosophy.[8] And legitimate stances on this concept do not even stop here. One can think of Ludwig von Mises' views on randomness as a *Probability-3*, explaining statistically random sequences of outcomes via algorithmic notions of recursive place selection.

Whatever one's final verdict, it seems uncontroversial that there are three main stances in the technical literature on information theories, which we dub

Information-A	Knowledge, logic, what is conveyed in informative answers
Information-B	Probabilistic, information-theoretic, measured quantitatively
Information-C	Algorithmic, code compression, measured quantitatively

Over-simplifying a bit, A is the world of epistemic logic and linguistic semantics, B that of Shannon information theory, linked to entropy in physics, and C that of Kolmogorov complexity, linked to the foundations of computation. We do not feel that these are opposing camps, but rather natural clusters of themes and research styles. Thus, we felt that all of these need to be represented in our Handbook, since only their encounter gives us the proper canvas for philosophical enquiry.

A first comparison

What are the paradigmatic informational scenarios described by these approaches? We start with a first pass, and draw a few comparisons.

(A) The typical logic-based setting lets an agent acquire new information about what the real world is like, through acts of observation, linguistic communication, or deduction. A simple example would be an agent asking a question, and learning what things are like from an answer. Thus, three features are crucial: *agents* which represent and use the information, *dynamic events* of information change, and *'aboutness'*: the information is always about some relevant described situation or world. Here, we measure quality of information qualitatively in terms of new things agents can truly say: a quantitative measure may be handy, but it is not required. Finally, the formal paradigm for the theory is mathematical or computational logic.

(B) By contrast, the typical Shannon scenario is about a source emitting signals with certain frequencies, say a 'language' viewed as a global text producer, and the information which a receiver picks up from this is measured in terms of expected reduction of uncertainty. This is the sense in which seeing a particular roll of a fair die gives me 3 bits of information. No specific agency seems involved here, but the scenario does analyze major features of communication which are absent on the logical approach, such as *probability* of signals (i.e.,

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[8] Carnap tried a similar move with 'information' in the early 1950s, juxtaposing Shannon's quantitative notion with his own qualitative logical information spaces. (Cf. [Kohler, 2001].)

the long-term behaviour of a source, maybe as viewed by the receiver), *optimal coding*, and *channel capacity*. Finally, mathematical paradigms for the theory are probability theory and physics.

Clearly, scenarios A and B are not mutually contradictory. They are about different aspects of sometimes even one and the same scenario of information flow, omitting some and high-lighting others. Still, the two stances meet at various points. For instance, coding systems relate to the efficiency of natural language (or lack thereof), signal probability relates to reliability of sources (also relevant to logicians), and Shannon theorists often use question-answer scenarios to motivate their notion, in terms of minimal numbers of questions to pin down the truth.

(C) Next, take the basic Kolmogorov scenario. We receive a code string, and ask for its informational value. The answer is the algorithmic complexity of the string, defined as the length of the shortest program that computes it on some fixed universal Turing machine. While this looks like a totally different setting from the preceding two, there is a direct link to Scenario B. Working with the enumerable set of all 'prefix-free programs', we can easily find an associated probability distribution.[9] In this way, the shortest program for a string becomes an optimal code in Shannon's sense. Thus the following 'traffic' arises: Information-B starts with the notion of probability as fundamental and derives an optimal code. Information-C starts with the notion of shortest code as fundamental and derives an a priori probability from it. Further details may be found in the chapters of Grünwald & Vitányi, Topsøe and Harremoës, and Adriaans in this volume.

Stating technical transformations between notions of information is one thing, understanding their philosophical consequences another. For instance, consider the following intriguing questions. What is the status of a computational device like a Turing machine in grasping the available information in Nature [Wolfram, 2002]? Does algorithmic complexity still apply if we go from computer code to datasets of observations? Is Nature a computing agent sending us encoded messages? To some computer scientists [Schmidhuber, 1997], Information-C is indeed the basis for a general theory of induction that commits us to 'metaphysical computationalism'.

Relations between Information-C and Information-A are even more delicate. The latter seems closer to information flow in human settings and purposeful activities. But here, too, some researchers see algorithmic data compression as a universal principle governing human-level information flow, leading to what may be called 'cognitive computationalism': the idea that the human brain is a universal computational device [Pinker, 1997; Chater and Vitányi, 2003; Wolff, 2006]. If an agent has background knowledge, in the form of optimal descriptions of a set of objects (e.g., animals), then identifying such an object (e.g., a cow) via a picture amounts to finding a shortest algorithmic description of the picture conditional on

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[9] By Kraft's Inequality, for any finite or infinite sequence $l_1, l_2, \ldots$ of natural numbers, there is a prefix code with this sequence as the lengths of its binary words iff $\sum_n 2^{-ln} \leq 1$.

that background knowledge. While not uncontroversial, this philosophical view, too, has interesting consequences, and even some degree of empirical support.[10]

This brief discussion may suffice to show that Information-A, Information-B, and Information-C make sense on their own, while engendering many intriguing interactions. As editors, we do not have a final view on the relation between these approaches, and whether a Grand Unification is possible. We do feel that they need to be compared in an open fashion, questioning even the usual labels 'qualitative' vs. 'quantitative'.[11] Our own sense, developed partly thanks to insights from our authors in this Handbook, is that B and C are close, while the relation to A-approaches is much less settled. Even so, the B scenario clearly shares some features with A-type views of information update, and thus one might view Shannon's theory as go-between for A and C. But still, we may have to 'do a Carnap' in the end, putting the three side-by-side, just as we saw with probability.[12]

4 THE CHAPTERS OF THIS HANDBOOK

This is a good point to interrupt the editors' story, and let another voice speak for itself, viz. the list of chapters of this Handbook. The idea behind its composition has been to put two things at the reader's disposal. One is a Grandstand View of serious studies of information in the various sciences, and the styles of work as done by leading practitioners. The other item offered are a number of major leads toward a philosophy of information, written by distinguished philosophers. The latter include both senses that we have described earlier: philosophical foundations of the information sciences, and also informational turns inside philosophy itself. We give some cameo descriptions, while also briefly 'presenting' the authors.

After this editorial Introduction, the Handbook starts with a first Part on *Philosophy and Information.* The opening chapter by Fred Dretske, a pioneer in bringing information theory to philosophy, discusses how the notion of information plays in epistemology, and merges well with current debates. Next, Hans Kamp and Martin Stokhof examine the role of information in the philosophy of language and the theory of meaning, drawing upon their long experience in philosophical logic and formal semantics at the interface of philosophy and linguistics. Pieter Adriaans, a classical philosopher turned machine learning expert (amongst other things), continues with major issues in the philosophy of learning, exploring in particular the knowability of the physical universe from a computational standpoint. Finally, Luciano Floridi, mentioned several times already, maps out

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[10] The most efficient current program recognizing musical styles uses algorithmic information theory [Cilibrasi and Vitányi, 2005]. Adriaans [2008] even proposes an algorithmic esthetics.

[11] Indeed, all three types can have more qualitative or quantitative versions, witness Carnap's Inductive Logic on the A-side, or the basic 'representation theorems' of Shannon information theory on the B-side.

[12] Indeed, von Mises third probability intuition in terms of randomness and computable 'place selection' does look a bit like an algorithmic Type C approach to information, through its links with recursion theory in the work of Per Martin-Löf, Michiel van Lambalgen, and others.

the broader agenda for a philosophy of information as he has been advocating it over the recent years.

Next comes a foundational part on *Major Technical Approaches.* Mathematicians Fleming Topsøe and Peter Harremoës give a lucid exposition of Shannon's quantitative theory of information and its embedding in general mathematics. Next, Peter Grünwald and Paul Vitanyi, leading theorists in the foundations of Kolmogorov complexity, statistics, and recently also quantum information, follow up with a state-of-the-art account of algorithmic complexity theory, including its connections with probability and Shannon information. Finally, logicians Johan van Benthem and Maricarmen Martinez, representing the different traditions of epistemic logic and situation theory, investigate the role of information in logic, and describe what this discipline has to offer by way of general theory.

Our third part, *Major Themes in Using Information,* zooms in on some key themes in the foundations of 'informatics'. Kevin Kelly, who has been instrumental in bringing topology and recursion theory to the philosophy of science, writes about learning, simplicity, and belief revision, with Occam's Razor as a running theme. Logicians Alexandru Baltag, Hans van Ditmarsch, and Lawrence Moss describe knowledge and information update as studied in recent 'dynamic epistemic logics', showing how informational themes are creating new logics right now. Hans Rott, one of the architects of belief revision theory, follows up on this with a formal account of how agents change their beliefs when triggered by new information, and discusses optimal cognitive architectures for this. Moving to other information-producing activities, Samson Abramsky, a leader in the current interest in 'information dynamics' in computer science, discusses the information flow in computation, drawing upon recent game-based models of interactive processes, with surprising connections to quantum information flow in physics. Information in games and rational agency per se is then discussed in depth by Bernard Walliser, an economist who has published extensively on the conceptual foundations of game theory.

The final part of the Handbook collects a number of representative case studies of *Information in the Sciences & Humanities.* Mike Dunn, logician, philosopher, computer scientist, and prime mover in the formation of Indiana University's School of Informatics, surveys the various uses of information in computer science, from Scott 'information systems' to algebraic theories of data structures and informational actions. Well-known physicists Sander Bais and Farmer then present a masterful treatment of the notion of information in physics, opening up to connections with Shannon information and Kolmogorov complexity. Information in the social sciences is represented by the chapter of Keith Devlin and Duska Rosenberg, who give an in-depth transaction model for linguistic communication using tools from situation theory. Next, John McCarthy, one of the founders of AI, surveys the uses of information in artificial intelligence, stressing the role of representation, context, and common sense reasoning, and throwing out a list of challenges to philosophers. The final two chapters move to the natural world of the life sciences. Margaret Boden discusses the role of information in cognitive psychology, including recent neuro-science perspectives. And the last chapter in our tour of Academia is John Collier's critical study of current uses of information and coding in biology, whose repercussions are all around us in bio-technology and its hybrids with computer science.

In addition to the authors, we should also mention the official commentators, who have played an important role in this Handbook. Each chapter has been read by its assigned commentator, and their extensive responses and the ensuing discussions have kept authors alert and fair to what has been achieved in their fields. The commentators behind this Handbook are as distinguished and diverse a group as our authors, including prominent philosophers, computer scientists, linguists, and psychologists, and their names will be found in the separate chapters.

Of course, no system is fool-proof, and as with every Handbook, the editors might have made some choices of chapters differently, while there are also bound to be strands in the field that remain under-represented. One can look only so far. Even so, we feel that the present collection provides ample material for substantial reflections, and in the rest of this Introduction, we present a few of our own.

5 INTEGRATIVE THEMES AND NEW QUESTIONS

When collecting the material for this Handbook we have toyed for a moment with the ambition of providing one unified account of information that would satisfy all our authors, and even a more general audience. While this has proved somewhat illusory at our current state of enlightenment, we do feel that we are now in a much better position to draw some main lines. Here are a few themes that we see running through many of our chapters, found not by looking top-down at what information should be, but bottom-up, looking at stable patterns in existing research. We start by re-analyzing the three streams we identified earlier, 'unpacking' these paradigms into a number of general themes that seem relevant to information generally. In this manner, we hope to find a unity through themes instead of 'all-in' packages.

Logical range and reduction of uncertainty

One simple, yet powerful theme in many of our chapters is this — and it may even be the common sense view. Information may be encoded in a *range of possibilities*: the different ways the real situation might be. For instance, at the start of a card game, the range consists of the different possible deals of the cards. Numerically, this view reflects in the standard representation of information in bits being the (weighted) base-two logarithm of the size of the range. More dynamically, on this view, new information is that which reduces my current range — that is: more information leads to a smaller range. This is the standard logical sense of information in which a proposition P *updates* the current set of worlds W to $\{w$ in $W|w$ makes P true$\}$. This notion is relative to a 'logical space' describing the options. It is also relative to agents, since the update happens to what they know about the world. In our reading, this is the main notion of information used in our Handbook chapters by Baltag, van Ditmarsch and Moss, van Benthem and Martinez, Dretske, Kamp and Stokhof, McCarthy, Rott, and Walliser. It is an A-type account in our earlier sense, which revolves around agents' logical spaces of alternative options, set up for some purpose (information is *"for"* something), zooming in on some yet unknown actual situation (the latter is what the information is *"about"*), and new information typically has to do with dynamic events of observation, communication or inference updating the current state.

Yet there are also links with B and C types of information. If a range of n messages has maximum Shannon entropy, the optimal code for each message takes $log_2 n$ bits. And as for update, if I know that John lives in Europe, I need some 30 bits to identify him, but after new information that he lives in Amsterdam this effort is reduced to 20 bits. And as to Information-C, the shortest program p for a string x in the sense of Kolmogorov complexity can also be interpreted as a measure for the smallest set of $2^{|p|}$ possible worlds that we need to describe x. Thus, 'range' truly seems an integrating feature across information theories.

Correlation and channel transmission

The next pervasive notion in our Handbook emphasizes another key aspect of information flow, viz. the correlation between different systems that drives it. One situation carries information about another if there is a stable correlation between the two. This is the sense in which dots on a radar screen carry information about airplanes out there. Note that this information may be there, even when there is no agent to pick it up.[13] In philosophy, this sense of information is central to the earlier-mentioned work of Dretske and Barwise and Perry, who were inspired by Shannon's paradigm, and who stress the essential 'situatedness' and 'aboutness' of information. Indeed, correlation seems of the essence there, and the view of information transmitted across less or more reliable channels is dominant in our chapters by Bais and Farmer, Boden, Collier, Devlin, Dretske, Kelly, Topsøe and Harremoës. One of its key features is that information is crucially *about something*, and thus a relation between a receiving situation and a described, or sending situation. In this scenario, the 'quality' of the information depends essentially on the reliability of the correlation. But it is also possible to find these same concerns implicit in our more 'A-type chapters'.

The two themes identified so far play in various fields. For instance, our chapter on logical theories of information finds range and correlation right inside logic, and shows how they are highly compatible there, combining into a single mathematical model. But also, Shannon's information theory contains aspects of both range and correlation. It is definitely about reducing ranges of uncertainty — in a quantitative manner asking for the *average* reduction of uncertainty, summarizing many possible update actions. But is also crucially about correlation between

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[13] Thus, unlike in the classic Procol Harum song 'Homburg', `http://www.lyricsdomain.com/16/procol_harum/homburg.html`, in situation theory, "signposts" do not "cease to sign" when there are no human beings left on our planet.

a source and a receiver across a channel. In algorithmic information theory the notion of correlation seems less pregnant at fist sight, as Kolmogorov complexity is a priori and universal, being a measure of 'self information' of a data set. But even there, in principle, it is always correlated with an abstract computational device, its source.[14] More technically, correlation between data sets and what they describe has been studied in terms of 'conditional Kolmogorov complexity', with the reference universal Turing machine providing the 'channel' in the above-discussed correlational sense.

Temporal dynamics and informational events

But there are further general themes in the A, B, and C stances that seem of general significance for information. In particular, the Shannon scenario and correlation generally, seems to presuppose a *temporal dynamics*. Information is not a one-shot relation between single events: it presupposes an objective pattern of matched events over time, and this frequency information is one essential function of the probabilities employed.[15] This temporal perspective is also in evidence on the logical side, and it even plays there in two different ways. Locally, the flow of information is driven by specific informational events that produce it, such as an observation, or an answer to a question.[16] But there is also a global long-term process of repeated observations, which establishes reliability and information flow in some higher sense. In computer science terms, the local dynamics calls for an account of stepwise informational actions, while the global dynamics calls for a *temporal logic*, or a statistical dynamical systems model, of long-term program behaviour over time. We have nothing to add to the latter feature here, but the local dynamics bears some separate discussion, since it seems intimately related to our very understanding of information. We start with the basic information-handling process, and discuss some generalizations later.

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[14] Again, this at once raises philosophical questions. Kolmogorov complexity claims to be a priori and objective. But the price is high: the notion is asymptotic and non-computable. Three key results from Turing govern this setting: (a) Enumerability: there is a countable number of Turing machines, (b) Universality: there is an unlimited number of universal Turing machines that can emulate any other Turing machine, (c) Undecidability: there is no program that can predict, for all combinations of input X and Turing machines M, whether M will stop on X. A universal Turing machine can be defined in less than 100 bits. Given all this, we can select a small universal Turing machine U on which any digital object O will have a shortest program. On the C-view, the length of this program will be the 'objective' amount of information in O. This program cannot be found by any effective computational process, because of point (b), but the work of Solomonoff, Kolmogorov and Levin shows that under certain constraints we may still use all this as an adequate information measure.

[15] Of course, these probabilities also have a subjective aspect, since they may be seen as describing agents' views of the situation.

[16] Note that performing an experiment is asking a question to Nature, cf. [Hintikka, 1973].

Information and computation

One can teach a course on information theory without mentioning computers, and conversely, one can treat computation theory without reference to information. Yet the interplay of information with computation as a way of producing or extracting it is subtle and challenging. Here is one issue which plays in several chapters of this Handbook. Due to the 'data processing inequality' (see [Cover and Thomas, 2006]) deterministic computational processes do not create information: though they may discard it. Thus, the amount of information in a computational system can never grow on B- or C-type views! Indeed, the only processes in our world that generate maximal information-rich sets are pure random processes like quantum random number generators. A string generated by such a device will with high probability have maximal Kolmogorov complexity. And yet, our world seems a very information-rich place, and clearly not all information is random. Many natural processes generate new information by a non-deterministic device under deterministic constraints. Thus, evolution and growth seem to create complexity 'for free', and though we can simulate them on a computer, the merit of these simulations in terms of the creation or annihilation of information is not clear. The chapters by Abramsky, Bais and Farmer, Topsøe and Harremoës, Floridi, and Adriaans contain a wealth of material shedding light on the general interplay of information and computation, but key issues like the one mentioned here are far from settled. It may call for a deeper understanding of connections between B- and C-type accounts with A-type accounts.

The process stance: information in action

Next, generalizing from computation in a narrower sense to cognitive activities of agents, let us develop a methodological idea from computer science — and philosophy — in its appropriate generality. In a computational perspective, it makes little sense to talk about static data structures in isolation from the *dynamic processes* that manipulate them, and the tasks which these are supposed to perform. The same point was made in philosophy, e.g., by David Lewis, who famously said that 'Meaning Is What Meaning Does'. We can only give good representations of meanings for linguistic expressions when we state at the same time how they are *used* in communication, disambiguation, inference, and so on. In a slogan: *structure should always be studied in tandem with a process!* The same duality between structure and process seems valid for information, and indeed, all of our stances, and al of our chapters, have specific processes in mind. *No information without transformation*! The logical A-stance was about information update, the Shannon B-view stressed transmission events, and the Kolmogorov $C-$view is all about computational activities of encoding and decoding. And these process scenarios are not just 'background stories' to an essentially static notion of information, they are right at the heart of the matter.

But then, *which processes* would be paradigmatic for the notion of information? The chapters of this Handbook show a great variety: from questions and answers

(Kamp and Stokhof), observations (Baltag, van Ditmarsch and Moss), communication (Devlin and Rozenberg), learning (Adriaans, Kelly), belief revision (Rott), computation (Abramsky), and inference (van Benthem and Martinez) to game-theoretic interaction (Walliser). And this list generates many questions of its own. What does information *do* for each process, and can we find one abstract level of representation for them that stays away from details of implementation? Also, some of these processes concern single agents, while others are intrinsically multi-agent 'social' events. Is the basic informational process a multi-agent one, with single-agent activities their 'one-dimensional projections'?[17] We will not attempt to answer these questions here, but we do think they are central to a philosophy of information that bases itself on the best available information-theoretic practices.

Information as code and representation

While the preceding tandem view seems to high-light the dynamic processes, it equally well forces us to think more about the details of representation of information. Here is where the linguistic study of natural language has much to offer (see our chapter by Kamp and Stokhof), in particular in connection with A-type views of information. In another setting, the chapter by Devlin and Rozenberg highlights subtleties of linguistic formulation in informational transactions in social settings. But other abstraction levels, even when far removed from 'meaningful discourse', carry insights of their own. Recall the mathematical fine-structure of our C-stance. The Kolmogorov complexity of a data set was the length of the shortest program that generates this data on a computer.[18] Now consider an apparently strange feature here, viz. the definition of *randomness*. A string X is random if it cannot be compressed, i.e., no program shorter than the length of X produces X on our universal Turing machine. Thus, random strings have the highest amount of information possible: say, a radio transmission that only contains noise! This runs head-long into the idea of information as 'meaningful'. But it does reveal an intriguing connection elsewhere, with thermodynamics as in the chapter of Bais and Farmer. Kolmogorov complexity can be viewed as a theory of string entropy, with random strings as systems in thermodynamic equilibrium. This suggest intriguing equivalence relations for translating between complexity theory and physics, for whose details we refer to Adriaans [2008].[19]

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[17] For instance, is 'learning' as in formal learning theories just a one-agent projection of a shared activity of a two-agent system {Learner, Teacher}? Likewise, is a logician's 'proof' as a formal string of symbols the zero-agent projection of a multi-agent interactive activity of argumentation?

[18] Here is one more common sense way to understand the different stances here. You are at an information booth at the airport, trying to book a hotel. The information in statements like "There is a room free in the Ritz", is probably best analyzed in A- or B-terms, but when the official shows you a city map that tells you how to get to the Ritz, something else is going on. The map contains information which can be measured: a detailed map contains more information then a sketch. The computer file that the printer uses to produce a detailed map contains more bits than the file for a large scale one. This is the structure measured by Kolmogorov information.

[19] Here is a summary. Consider these 'identities': (a) Length $|x|$ of a string $x \approx$ the internal energy U of a system, (b) Kolmogorov Complexity $C(x) \approx$ Entropy S of a system, (c) Ran-

This concludes our list of general themes, showing how systematic reflection on the various stances in information theory raises questions of interest to all.

6 CONCLUSION, AND THE PURPOSE OF THIS HANDBOOK ONCE MORE

The main scientific ingredients

This Handbook presents a panorama of approaches to information, drawing for its methods on at least three major scientific disciplines: *logic*, *computer science*, and *physics*. It might be thought that all of these strands have already been integrated in current broad academic 'informatics' environments, but this seems more of a hope than a reality so far. In particular, while it is true that, over the 20^{th} century, computer science has yielded a host of fundamental insights into the representation and processing of information,[20] its foundations remain an exciting open field. It may even be true eventually that the complete scientific background for the foundations of information should include *cognitive science*, but we have not chosen this as major focus in our scheme yet — though we do have chapters by Boden on information in cognitive science, and Collier on biology.

From unification to co-existence

What we have not achieved in this Handbook is a Grand Unification of all major technical approaches to information. We do not know if one is possible, and we sometimes even wonder whether it would be desirable. What does happen here is that different bona fide traditions meet, and what we hope will happen is that they find a common language, and a research agenda including new shared concerns. We think this is possible because our analysis in the preceding sections, largely based on the contents of this Handbook, has not revealed incompatibility, but rather a *complementarity* of perspectives.

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domness deficiency $|x| - C(x) \approx$ the Helmholz free energy $U - TS$ of a system (T = absolute temperature), (d) Random string $\approx$ system in equilibrium. Here the randomness deficiency of a string is its length minus its Kolmogorov complexity, just as the free energy of a system is the internal energy minus its entropy by equal temperature. Free energy is linked with meaningful information. A system in equilibrium cannot do any work, just as a random string does not contain any meaningful information. Thus the meaningful information in a string may be defined as follows. The *facticity* $F(x)$ of a string x is the product of the normalized entropy $C(x)/|x|$ and the normalized randomness deficiency $1 - (C(x)/|x|)$. The term is motivated by Heidegger's notion of 'die unbegrundbare und unableitbare Faktizität des Daseins, die Existenz..." [Gadamer, p. 240]. If p is the shortest program that generates x on U, then p is by definition a random string. Nothing can be said about it or derived from it other than that $U(p) = x$. The string p is completely meaningless outside the context of U. Kolmogorov complexity maps all meaningful strings on to meaningless random strings.

[20] Just think of automata theory, complexity theory, process theories, AI: the list is impressive, and it immediately belies the modest 'handmaiden' role that some want to relegate the field to.

Successful merges

Concrete examples of the potential for merging will be clear to any serious reader of our chapters — if only, because many ingredients of one paradigm make immediate sense in another. For instance, one might, and probably should, introduce correlationist information *channels* in a more realistic logical range view, and several proposals to this effect were made recently. Or, our chapter on Shannon theory involves questions and answers at crucial stages, and introducing explicit *dynamic multi-agent* perspectives in B- and C-type accounts of information might be worth-while. This would reflect a recent general move toward studying 'interaction' as a basic phenomenon in the foundations of logic and computer science. But many further desiderata emerge from the material collected here. For instance, various chapters make surprising new moves towards *physical models* of information, including those by Abramsky and Adriaans. This connection seems important, and it might lead to possible new academic alignments. Finally, even the austere code-based view of information really occurs throughout this book, witness the chapters on natural language, on computation, and on logic. Indeed, the latter discusses the related 'scandals' of computation and deduction: which reflect long-standing philosophical discussions. How can a code-based process of valid computational or inferential steps generate information? How can we harmonize algorithmic and semantic views? The reader will find some answers in the relevant chapters, including links to the foundations of logic, Hilbert's proof theory, and Gödel's completeness theorem — but again, the issue is far from settled.

Indeed, fruitful combinations of the different perspectives in this Handbook already exist. Useful combinations of logical range spaces and Shannon-style correlation measures co-exist in modern semantics for natural language: cf. [van Rooij, 2004] on questions and answers, or [Parikh and Ramanujam, 2003] on general messaging. Indeed, a recent special issue of the *Journal of Logic, Language and Information* [van Benthem and van Rooij, 2003] brought paradigms together in the following simple manner. Just consider one basic informational scenario like a question followed by an answer. Now ask a logician, an information theorist, and an algorithmics expert to analyze the very same scenario. It was highly instructive to see what features they picked up on as important, but also that, despite their differences in concerns and methodology, no deep contradictions arose.[21]

Creative tensions

Indeed, fostering some residual differences can be creative. Consider the editors themselves. Their 'gut views' on information are different. Adriaans is on the quantitative side, van Benthem on the qualitative one. At first sight, this seems a sharp divide. Scientists and engineers love computation, since we can now 'compute with information'. Philosophers and logicians feel that all the content and

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[21] See also [Kooi, 2003] for a case study of strategies for question answering combining ideas from logic, probability theory, and information theory in a practical manner.

drama of an informational event is 'flattened' into a one-dimensional number. Messages with totally different content can become equivalent in this way.

But this difference in direction can easily become a productive force. Even from a logical point of view, adding numerical measures seems relevant and natural, and many hybrids exist of logical and probabilistic systems for various cognitive tasks. Thus, there are already many areas of fruitful confrontation between logical and quantitative, often probabilistic methods. Consider evolutionary game theory or current methodological debates in ethics, where the role of norms and moral behaviour can be analyzed either in traditional logical terms, based on conscious reasoning from moral principles,[22] or as inevitable statistical equilibrium behaviour in large-scale long-term populations. Indeed, from a more practical viewpoint, Adriaans [2007] points out that in most realistic scenarios involving informational events, logical micro-descriptions are either unavailable, or the cost of computing them becomes prohibitive. In that case, the statistical approach is *the only way we have* of finding essential macro-features of the relevant process. The same might be true for information on a large scale and in the long run — and here, despite the, perhaps, one-dimensionality of the numerical bit measure, it has amply shown the same 'unreasonable effectiveness' that mathematics has for Nature in general.[23]

Philosophy of information once more: two levels of ambition

Let us now take all this back to the title theme of this Handbook. The same difference in perspective that we discussed just now may be seen in the different scenarios discussed throughout this Introduction. And here is one way in which the editors have come to see it. Information plays at quite different levels in our human and natural world. One focus for many of the scenarios discussed here are episodes from our daily cognitive practice: language use, observation, communication, or other interaction between agents. Logical and linguistic models of information used by agents in small situations, acting on their private intentions, are meant for this fine-structure of informational transactions. But around all these private episodes, there is the global physical universe that we live in. And another highly significant question is the amount of information that we can hope to extract from that in our theories. At this level, single agents with their private purposes are totally irrelevant, and we are interested only in the large-scale structure of learnability. And the latter question seems to fit much better with the abstraction level provided by Kolmogorov complexity, where we can think of the universe as the output of a single Turing machine producing all data that we see.

In line with this distinction, we also see a distinction between philosophical themes connected to this Handbook. Agent-oriented episodes of meaningful A-type information flow seem closer to the concerns of epistemology today, and what people may be said to know about specific issues, perhaps kept from slum-

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[22] Cf. Kant's Categorical Imperative, or Rawls' initial scenario in "A Theory of Justice".

[23] This discussion of aggregation levels does show the importance of probability to our Handbook, and we might give the logic/probability interface even more attention in future editions.

bering by skeptics. Several chapters of our Handbook show what clarification arises from making information a major concern here, tying in to fundamental questions about the nature of knowledge, language, and logic. In contrast to this, global knowability of the universe in terms of its information content comes closer to the Grand Questions of the classical philosophical tradition, and asks what we could achieve in principle through observation and theory formation. Taking the mathematical perspectives in this Handbook seriously raises fundamental issues as well, this time, involving the nature and reach of the computationalism implicit in both B-type and C-type views. Is it more than just a convenient methodology? We have briefly discussed some positions in our earlier list of general themes, from metaphysical computationalism about nature to cognitive computationalism about human agents, though of course much more could be said.[24]

While all this may sound like a new-fangled 'technological' view, we see the roots of computationalism in the history of philosophy, going back at least to Descartes' mechanistic analysis of the 'res extensa'. Indeed, it still shares some of the weaknesses of that tradition — but there is also one obvious gain: the precision and clarity provided by the sophisticated mathematical models now at our disposal. Both strengths and weaknesses of philosophical claims can now be stated and investigated in ways that were simply unavailable before.[25] For instance, even if the whole universe can be simulated on a simple Turing machine, given enough time, this does not yet imply a *simple* model. The 'Turing Machine of Nature' could still be a universal computational device of any finite complexity.[26]

Now our point with these final thoughts should not be misunderstood. We are not saying that somewhere above the local level of informational episodes in daily life, and even beyond the whole history of science, there lies some Platonic reality of learnability that we can grasp a priori, making detailed studies redundant. What we do want to say is that the tools in this Handbook allow us to think about both the 'small questions' of philosophy, concerning language use, knowledge, belief, and reasoning of single agents, and the 'big questions', about the intelligibility of the universe, and what we can hope to achieve by collective enquiry.

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[24] Many pioneers of computer science have implicitly endorsed metaphysical computationalism. 'The entire universe is being computed on a computer, possibly a cellular automaton' according to Konrad Zuse (cf. [Zuse, 1969]). Similar views have been considered by John Archibald Wheeler, Seth Lloyd, Stephen Wolfram, Nick Bostrum, and many other serious thinkers.

[25] For instance, identifying computability with recursiveness, we can assign an objective, though inevitably non-computable information measure to all objects/messages in this universe. This is precise computational metaphysics. Of course, this, too, has its presuppositions, which might be questioned. How harmless is the choice of a Universal Turing machine, defined up to a 'constant factor'? Could even a leeway of 100 bits prevent us from using Kolmogorov complexity for the analysis of human intelligence? (Our brain has roughly 10^{15} neurons.)

[26] Moreover, the point at which Kolmogorov complexity asymptotically approaches the actual complexity of objects in our world might lie well beyond a horizon that is useful and practical.

Philosophy of information: some major issues

To summarize, we list the broad research issues emerging in this Handbook that we see as central for the development of the field:

1. *Information per se.* What is information? Is there one general notion that encompasses all others, or do we merely have a family of loosely related concepts, or perhaps 'complementary stances' in practical settings, making the peaceful co-existence of approaches as described in this editorial the best that can be achieved?

2. *Information and process.* What is the relation between information structure and computation, deduction, observation, learning, game playing, or evolution? These processes seem to create information for free. How to understand this? Can we unify the theory of information, computation, dynamic logics of epistemic update and belief revision, and the thermodynamics of non-equilibrium processes?

3. *Information and philosophy***.** The chapters in this Handbook tie the notion of information to fundamental issues in classical philosophy, 'analytical' but equally well 'continental'. Can we 'deconstruct' classical philosophy with modern information-theoretic tools, and bridge the culture gap between the two traditions? The tools of logic and mathematics at least have no bias for one over the other.[27]

Thus, though this Handbook is full of answers to anyone interested in a serious study of information, we end with open questions, as true philosophers should.

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[27] Incidentally, Adriaans comes from the continental tradition, van Benthem from the analytical one, though their paths have crossed repeatedly in logic and mathematics.

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