Preface

> We have found a strange footprint on the shores of the unknown. We have devised profound theories, one after another, to account for its origins. At last, we have succeeded in reconstructing the creature that made the footprint. And lo! It is our own. (Eddington [1, p. 200])

> No element in the description of physics shows itself as closer to primordial than the elementary quantum phenomenon, that is, the elementary device-intermediated act of posing a yes-no physical question and eliciting an answer or, in brief, the elementary act of observer-participancy. Otherwise stated, every physical quantity, every it, derives its ultimate significance from bits, binary yes-or-no indications, a conclusion which we epitomize in the phrase, 'it from bit'. (Wheeler [7, p. 309])

This volume was inspired by an FQXi-funded conference held at Trinity College, Cambridge (March 20–23, 2014).[1] This led to additional work over the subsequent two years that addressed the questions raised at the conference in greater detail. The basic premise of the full research programme was that the 'practical' approach to information (as a resource to be manipulated), while certainly very impressive and fruitful, has radically outpaced our theoretical understanding. Yet, advances in quantum information and other related areas have begun to push the boundaries of the physically possible and suggest new ways of thinking about reality, making a foundational understanding of information increasingly important for future progress and, perhaps, yet more impressive practical outcomes.

Our aim was to take our cue from the later ideas of Arthur Eddington[2] and John Wheeler in an effort to fill in some of the empty theoretical ground. To both Eddington and Wheeler, though their views certainly differed in a great many ways, information occupied a (in fact, *the most*) fundamental position in the order of things. Physical reality, in their view, is shaped by the questions we choose to put to it and is thus built up from the information thus generated. This is the root

[1]Details can be found here: https://informationandinteraction.wordpress.com.

[2]By 'happy' coincidence, the conference that inspired this work coincided with the 70th anniversary of Eddington's death.

of Wheeler's famous phrase 'it from bit', which is taken to anthropic extremes in his (rather less famous) 'self-excited circuit' in which all of physical reality (including seemingly paradoxically, ourselves, qua beings of a certain constitution) is determined by the questions of observers whose decisions determine (to some extent) facts as to what has happened and what will happen. The observers (or, less anthropically loaded, the observational equipment involving some irreversible process) play an active, creative role in defining reality[3]:

> 'it from bit' symbolizes the idea that every item of the physical world has at bottom—at a very deep bottom, in most instances—an immaterial source and explanation; that what we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and this is a participatory universe. [9, p. 311]

Observers themselves (and so the *interaction* of observer and observed, or subjective versus objective) also play crucial, though again rather different, roles in their work. Neither of them privileged observers as *external* to physics, but sought to incorporate them in the description provided as ineliminable actors. In Wheeler's case (in his anthropic 'observership scheme'), observers were at the root of existence. In Eddington's case, observers merely 'selected' aspects of reality rather than creating them as such—by including observers we must take seriously the intrusion of certain biases into our mathematical theories of reality such that any theory will contain a fair portion of material that reflects certain of our features as experimenters/observers (under various constraints) rather than objective reality. This leads directly to Eddington's much maligned *a priorism*:

> An intelligence, unacquainted with our universe, but acquainted with the system of thought by which the human mind interprets to itself the content of its sensory experience, should be able to attain all the knowledge of physics that we have attained by experiment. [2, p. 3]

In other words, physics is, for Eddington, partly an exercise in 'observer-spotting': there exist (anthropic) selective aspects that are those parts of a physical theory that are really contributions of the intellect and our constitution as observers and measurers of the world. Hence, there is a kind of anthropic carving of reality in both Wheeler and Eddington that can be distinguished by the powers given to the observers asking the questions and making the decisions: in the former, there is a creation of new facts and in the latter, a selection of facts.

One can gain a better understanding of the connection between Eddington's views and those of Wheeler by looking at the work of Wheeler's student (and long-time friend) Peter Putnam. Putnam was amongst the students who joined Wheeler in Leiden in 1956 when Wheeler was at the beginning of his career in general relativity. Wheeler had supervised Putnam's A.B senior thesis on

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[3]For Wheeler, observers as passive recipients or 'registers of facts' should be replaced by 'participators': there is no 'ready-made universe' to simply record (see, e.g. [8, p. 286]). Eddingtonian observers are likewise non-passive, though they act on a pre-given objective realm, selecting (not necessarily consciously) certain portions as if those portions exhausted what reality is.

Eddington (completed in 1948 at Princeton), but was not very impressed with his academic abilities [9, p. 254]. While Wheeler spoke of disabusing him of his Eddingtonian belief that the laws of nature can be deduced by pure reasoning, it seems Putnam possessed a certain charisma, and it is not unreasonable to believe that certain Eddingtonian principles trickled into Wheeler's thinking. Putnam apparently did drop Eddington for physics, but later drifted into a bizarre mixture of psychology, linguistics, philosophy, and physics—during this time, as Wheeler relates, Putnam was making money as a janitor (rejecting his family's considerable wealth). But Wheeler remained friends with Putnam until Putnam's death in the late 1970s.

In his large, unpublished manuscript 'Comments on Eddington' (from 1962, with a preface added in 1971[4]), Putnam integrates the Wheeler–Everett many worlds interpretation with Eddington's *Fundamental Theory* and his general philosophy, as outlined in *The Philosophy of Physical Science*. In the preface, Putnam writes that he spent a decade (1962–1972) figuring out how to embody an Eddingtonian lifestyle (a 'world outlook'). It seems that Putnam was concerned with getting a physics that could cope with the 'felt real' (with the experience of observers). He wanted a universal science—indeed, perhaps some of the problems people have had with Eddington's later work is that they are trying to force it into the mould of physics, when some of it clearly is not quite physics. Putnam is certainly correct in saying that Eddington's approach is 'not physics in its usual sense' (p. 2), and he in fact viewed its significance as lying in the treatment of the brain (or observer) as a parallel calculating machine: that is, as **a device that deals in information**. In other words, it is sub-physics, and is therefore supposed to say something about the operations that physicists themselves carry out: physics (*the* fundamental theory in Eddington's sense) involves, then, a study of the operations of the calculating machine (us) and has information and interaction at its centre. Hence, Eddington was not concerned with a description of the world independent from observers (the 'absolute world'), but with the description of our means of interacting with it and gaining information: the observer could not be removed from scientific practice.[5] Putnam believed that this incorporation of the observer into physics resolved certain philosophical problems that led to considerable conceptual confusion. This centrality of the observer also brings information and interaction centre stage, as we have discussed, and that is this book's focus.

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[4]Downloadable at: http://peterputnam.org/comments_on_eddington_1962_preface_1971.htm. It seems Putnam could not let Eddington go so easily. However, the essay is by no means hero-worship, and Eddington takes much flack in this work.

[5]Whether this was in fact Eddington's view is not what concerns us here. Rather, it is the link to Wheeler's 'it from bit' idea. The link seems to be especially strong when it comes to the measurement process, and the idea that this should itself be part of physics so that the subjective and objective are reconciled. Putnam, as mentioned above, related this directly to the Everett–Wheeler view in which the measurement process itself (involving human observers, as a matter of fact, but not in any supernatural way) should be included as part of physics.

Wheeler pushed the notion of measurement and the role of the observer into territory easily as uncharted as Eddington. In the context of the delayed-choice experiment, for example Wheeler envisages a scaled-up version involving photons having travelled a billion light years from a quasar, separated by a ‘grating’ of two galaxies (to act as lenses offering two possible paths for the light), to be detected at the Earth using a half-silvered mirror at which the twin beams can be made to interfere. For Wheeler, this means that the act of measurement (our free choice) determines the history of that entire system: actions by us NOW determine past history THEN (even billions of years ago, back to the earliest detectable phenomena, so long as we can have them exhibit quantum interference). It is from this kind of generalization of the delayed-choice experiment that his notion of the Universe as a ‘self-excited circuit’ comes: the Universe’s very existence as a concrete process with well-defined properties is determined by measurement. Measurement here is understood as the elicitation of answers to ‘Yes/No’ questions (e.g. did the photons travel along path A or B?): bit-generation (gathering answers to the yes/no questions) determines it-generation (the universe and everything in it). However, Wheeler’s notion does not privilege human observers, but rather simply refers to an irreversible process taking uncertainty to certainty.

The Eddington–Wheeler link can be made a little more precise through the notion of *idempotency*. An operator A is said to be idempotent if $A^2 = A$. Idempotent operators have eigenvalues of 1 and 0, corresponding algebraically to yes–no (bit-based) logic. Eddington employed idempotency at a somewhat deeper level (superficially, at least) than Wheeler, attempting to latch on to the fundamental structure of physics (and knowledge). Eddington used idempotent operators to mathematically define a notion of *existence* (and non-existence). In this way, Eddington defined the elemental structure of reality (true, basic individuality), and it maps closely onto Wheeler’s understanding: what is elemental is the yes/no logic (to be or not to be, that, in this case, is the answer!).

The phrase ‘it from bit’ can be a little misleading, then, since it suggests something static and eternal: whatever*is* (i.e. that which exists) is made from information. But that does not capture what is really going on. The idea embodies a*creative* principle. The settling of questions about the quantum world via measurement interactions creates facts about the world. There is here a curious amalgamation of Bohr’s teachings with Eddington’s. We think that these links, and the deeper meaning of ‘it from bit’ (as the genesis of reality, or facts, from observership), have yet to be explored sufficiently and hide many more secrets.[6]

It is worth noting here that, though Eddington’s later work was much maligned in its day, and continues to be misunderstood by a great many authors, many of his ideas have proven to be particularly prescient in retrospect. For instance, the ‘statistical’ portion of *Fundamental Theory*, comprising the first six chapters, is essentially one of the earliest attempts to develop a rigorous theory of reference

[6]As Helge Kragh explains in his chapter, Eddington restricts the ‘its’ to the laws and constants (pure numbers) of physics.

frames that incorporates elements of quantum theory with the geometric spirit of relativity by applying quantum mechanical uncertainty to the origin of spatiotemporal reference frames. There has recently been a resurgence of interest in the relationship between quantum mechanical principles (including the uncertainty relations) and the geometrical aspects of reference frames, most notably within the fairly new field of relativistic quantum information.

More specifically, Marco Toller began considering some of these very ideas in the late 1970s [6], many of which were later taken up by Carlo Rovelli who incorporated them into his relational interpretation of quantum mechanics [4, 5] which is decidedly Eddingtonian in spirit. Peres and Scudo even considered how one might utilize a quantum system to transmit information about a Cartesian frame [3], which is spiritually very close to Eddington's statistical ideas. This raises the issue of one particularly misunderstood aspect of Eddington's work. Superficially, if one only engages with his *Fundamental Theory* or *Relativity Theory of Protons and Electrons*, one might be tempted to assume that Eddington attached an certain objective/ontological status to some of his conclusions. If one, however, studies his *Philosophy of Physical Science*, it becomes evident that his view is decidedly subjective and epistemological. Indeed, he often refers to his view as 'selective subjectivism'.

While Eddington was relatively isolated towards the end of his career, Wheeler continued actively collaborating throughout his life. In fact, he actually worked directly with one contributor to this volume (Wootters). As such, his views on these topics have benefited from contemporary analysis and clarification, i.e. from an active engagement by the physics community while he was still formulating his views. Eddington, by contrast, had very little contemporary engagement with his theories. In some ways, this was because Eddington was simply well ahead of his time.

In any case, the chapters that follow engage with many of these same deep issues of information and/or observership interaction that float atop them: often we find that (what were thought to be) objective/ontological features of the world are bound together with subjective/epistemological features of observers.

That being said, Durham, in Chap.1 of this volume, argues that for science to have succeeded so dramatically, some objective aspects of reality must exist (in a later chapter, Fuchs argues that QBism actually allows for some level of realism). He argues that this objective aspect is embodied in physical laws themselves which are inherently relational in nature. This may seem counter-intuitive given that we have just argued that relational structures are subjective/epistemological, but Durham makes the case that some of those relational features are actually objective. Mathematics, being the way in which we describe these laws, is thus best viewed as a language of description rather than in a purely Platonic or formalist light. Durham further argues that mathematics actually arises from physics rather than the other way around, which bears some similarity to constructor theory, as described in Marletto's chapter. In this sense, Durham places Wheeler's 'it from bit' in the context of mathematical representation while holding to Eddington's dictum that we not lose sight of the original physical or logical insight that led us to a particular mathematical deduction in the first place.

Fully understanding the nuances in Eddington's thinking, however, requires going a bit deeper than mere science. Indeed, as Putnam has noted, Eddington's work was more than mere physics. Stanley, then, examines some of the modes of thought, both about science and religion, that prove useful in understanding Eddington's thinking in this regard. In particular, he emphasizes the importance of experience to both science and religion for Eddington who was a devout Quaker. Quakerism, unlike many other religions, is notably rooted in the non-dogmatic experience of the individual and thus, like physics, places the observer at the centre.

Of course, there is the traditional view that sees Eddington's *Fundamental Theory* (which, it should be noted, was posthumously assembled from his collected notes) as an early attempt at a 'theory of everything' (unifying quantum physics and relativity, as well as the large and small). Kragh offers a wide-ranging discussion of Eddington's work within this context. As he explains, Eddington's fundamental theory was so constructed that the laws and constants, derived as they were from epistemological considerations, could not be ruled out experimentally. But that was precisely the problem that most physicists had with it!

Like Kragh, Rickles' essay deals with the interpretation of Eddington's subjectivism and *a priorism*, taking his lead from Edmund Whittaker's[7] more lenient approach, focusing on the underlying general principles, rather than the specific applications in the computations of pure numbers of physics. He attempts to show how some sense can be made of them if cast in more modern terms, issuing primarily from quantum gravity research and the discussion of observables. Rickles shows that the more radical epistemological claims are not quite right, since observation (or a *plan* of observation/measurement by an observer) still lies at the root of Eddington's version of a priori knowledge: a priori is, for Eddington, tantamount to 'observer-spotting'.

But this volume is more than merely a reanalysis of Eddington and Wheeler themselves. It is an exploration of the ideas and spirit that their work embodied. As such, Weinert proposes that both local and cosmic arrows of time are theoretical constructions (inferences) from available information (criteria), in complete agreement with the Eddington–Wheeler epistemological approach. While attempts to identify the arrow of time (or arrows of time) with particular physical processes have often led us astray, Weinert argues that there are numerous criteria which allow us to infer the anisotropy of time.

Chiara Marletto then lays out the constructor theory (jointly developed with David Deutsch). There are many elements that bear close resemblance to features of Eddington's philosophy in this approach, not least of which is the use of 'principles'. In the case of Eddington, we find that the qualitative laws (relating to our constitution as observers) have the form of prohibitions on certain operations (what

[7]It was Whittaker who assembled Eddington's notes after his death and published them as *Fundamental Theory*.

Edmund Whittaker refers to as 'postulates of impotence'—see Rickles' chapter). In developing constructor theory, Marletto addresses a curious aspect of information (as ontology): it seems to be rather an abstract thing, independent (to a large extent) from specific physical objects (what she calls 'substrate independence of information'). This is in contrast to Wheeler's view that the information, in the form of bits, literally *was* the substrate of universe. The fundamental principle of constructor theory, then, is that every physical theory is expressible via statements about what physical transformations (tasks) are possible (or not possible) and why. In other words, counterfactual statements are taken to be fundamental as opposed to factual statements.

By way of a selection of relevant correspondence, Chris Fuchs tackles aspects of Wheelerian observership and takes seriously the idea of 'No participator, no world!' As Fuchs points out, Qbism (the approach Fuchs has pioneered with a variety of collaborators) owes much to Wheeler's later thoughts on the meaning of quantum mechanics. Fuchs battles with similar foes to Eddington and Wheeler before him: if agents/observers are central to the interpretation of the theory, then doesn't it lose it's realist character? Isn't it too subjective? Isn't it instrumentalist, positivist, or perhaps operationalist? Fuchs argues that the intrusion of 'the subjective factor' (into the interpretation of quantum states) by no means pushes the view into anti-realism: including the observer ought not to be tantamount to anti-realism. Indeed, this is akin to Eddington's 'selective subjectivism': objective reality exists but our knowledge of it is subjective (contrast this with Durham's views as outlined in Chap. 1).

Constructor theory and QBism can then be contrasted with a more operational 'agent-based' (or 'task-based') approach to physics ('resource theory') presented by Younger-Halpern, in which the experimentalist and their freedom to act on and influence a physical system (under some constraints), are centre stage. For example, a classical agent would be constrained to perform only local operations and would thus have a hard time creating entangled systems. The restrictions on agents' abilities (what kinds of operations they can carry out) determine theories from this resource perspective. Younger-Halpern lays out the basic project and advances various challenges and possibilities for the approach, including (as did Fuchs, in a different way), the issue of scientific realism with respect to such approaches.

As we mentioned earlier, this volume benefits from the fact that one contributor—Wootters—worked directly with Wheeler. In the past several decades, it is then no surprise that Wootters has been one of the leaders in the struggle to 'reconstruct' quantum mechanics from first principles. The approach he takes in this particular work is based on the fact that in order to do physics, we need to connect the entities that appear in our physical theories to the objects that we experience in the actual world. This ties in nicely with some of the earlier chapters that emphasize the experiential nature of reality. The core of Wootters' argument is a toy model that gains a non-trivial probabilistic structure from the imposition of a principle that he called 'the maximization of predictability'. In a way, he echoes Leibniz's assertion that we live in the best of all possible worlds, i.e. the world is best in the sense of being the most predictable in the face of an underlying randomness.

Though he never worked directly with Wheeler, Knuth was partly inspired by him to reconsider what one might usually think of as a paradigm of elementarity and objective individuality: the electron. He develops a view (‘Influence Theory’) according to which the relationship of the observer and the observed is far more widespread than, for example, notions of length measurements in the context of special relativity. Many of the (supposedly intrinsic) properties of the electron are argued to be relational, holding between the observer and the observed system (the electron), with a simple direct, discrete influence relation mediating their interaction. Hence, the respective shares played, in our physical description of the world, by observer and observed is, according to this model, not quite as simple as most simple accounts of scientific representation would have us believe (as with Eddington’s, Wheeler’s, and others from this volume).

This collection of papers only scratches at the surface of the rich body of work that exists and that shares a singular spiritual (and sometimes direct) kinship to the work of two titans of twentieth-century physics. Indeed, Eddington and Wheeler provide appropriate bookends for the greatest century in the history of physics: in many ways, they held similar views while in others they were diametrically opposed. On the one hand, both insisted that the role of the observer was crucial to our understanding of physics. On the other hand, it could be argued that Wheeler did not believe in an objective reality while it was quite clear that Eddington did.

Either way, it is our hope that this volume will stimulate further discussion and debate concerning the role of the observer in physics, the nature of our subjective relationship with the universe, and the nature and role of information in regards to both. As Wheeler once said,

> At the heart of everything is a question, not an answer. When we peer down into the deepest recesses of matter or at the farthest edge of the universe, we see, finally, our own puzzled faces looking back at us. (John Wheeler, as cited in John Horgan, The End of Science, p. 84 (Little, Brown & Company, 1998).)

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