Bit from It

Julian Barbour

Abstract

With his aphorism 'it from bit', Wheeler argued that anything physical, any *it*, ultimately derives its very existence entirely from discrete detector-elicited information-theoretic answers to yes or no quantum binary choices: *bits*. In this spirit, many theorists now give ontological primacy to information. To test the idea, I identify three distinct kinds of information and find that *things*, not information, are primary. Examination of what Wheeler meant by 'it' and 'bit' then leads me to invert his aphorism: 'bit' derives from 'it'. I argue that this weakens but not necessarily destroys the argument that nature is fundamentally digital and continuity an illusion. There may also be implications for the interpretation of quantum mechanics and the nature of time, causality and the world.

Contents

1 Introduction

Quantum information theory has suggested to numerous researchers that the ground of being – ultimate reality – is information. John Wheeler [1] is the prophet of this movement. Vlatko Vedral [2] argues that "information is physical", and Paul Davies [3] suggests that information is 'real' and "occupies the ontological basement". Both argue that information is more basic than quantum fields or energy. Moreover, in line with Wheeler's 'it from bit', they take information, and with it reality, to be digital and to rest ultimately on the answers to yes/no questions. Continuity is an illusion.

To see if such proposals are likely to be correct, we need a definition of *information*. What is it? This is the first issue that I address. I distinguish three kinds of information: as defined by Shannon, as used in normal language, and as intrinsic semantic information. On this basis, I conclude that ontological primacy should not be given to information but to *things*, as has always been the standpoint of realists.

I also find it important to define 'bit' and 'it'. Wheeler's 'bit' is strictly something that belongs to our perceptions, while an 'it' is something like a quantum field or particle whose existence we deduce from a pattern of perceived bits. Consideration of everything involved in the deduction process, in which the nature of explanation plays an important role, makes me question Wheeler's contention that every 'it' derives *its very existence* from bits. I find no reason to reverse the standard assumption of physics, namely that what we experience can be explained by the assumption of an external world governed by law. On this basis, Wheeler's aphorism should be reversed: 'bit' derives from 'it'.

An important part of my argument relates to the nature of a thing, which I argue is necessarily holistic and must be complete. The definition of a thing then amounts to a description of the universe from a particular point of view. At the end of my essay, I consider how this bears on the interpretation of quantum mechanics and the nature of time and the world.

2 General Comments

A symbol can stand for *anything*, but it must stand for *something*. Thus, x can stand for the position of a particle, and the digit 1 can stand for one apple, one pear, etc. Otherwise 1 is just black ink on white paper – and that too is something. This is important because Wheeler argues that "rocks, life, and all we call existence" are based on immaterial yes/no bits of information. It is a mistake to believe that the digits 0 and 1, being abstract, represent the immaterial. Quite to the contrary, I shall show that they stand for something quintessentially concrete.

My arguments rely on definite meanings of 'real' and 'existing'. Here it is necessary to distinguish what we experience directly from things that we hypothesize to explain what we experience. I know my conscious experiences are real and exist because I have direct access to them. Bishop Berkeley's maxim "To be is to be perceived" applies. Berkeley argued that, even as scientists, we do not need to postulate a real world behind experiences. This is the philosophy of idealism. According to it, the proper task of science is merely to establish the correlations between experiences. However, the success of theory in science suggests rather strongly that assuming the existence of things that we cannot see to explain things that we can is a good strategy. A striking early example comes from ancient astronomy. Greek astronomers observed intricate motions of the sun, moon, and planets on the *two*-dimensional sky. They explained them – saved the appearances – by positing simple regular motions of the celestial bodies in *three* dimensions. The success of the enterprise, brought to a triumphant conclusion by Kepler [4], justified belief in the reality of the assumed motions and extra dimension. Many more examples like this could be given. The findings of science are always provisional, but my position is that something that one does not directly observe exists if it explains phenomena.

3 Kinds of Information

It is perhaps a pity that Shannon's *The Mathematical Theory of Communication* [5] somehow morphed into *information theory.* That gives rise to potential confusion between three different meanings of 'information'. Let us distinguish them carefully.

The first is *Shannon information*, which he also called entropy or uncertainty. It involves *things* (which Shannon called messages) and *probabilities* for those things. Both are represented abstractly, the things by symbols (in practice binary numbers) and the probabilities by numbers. In line with what I said about abstraction, the symbols have no meaning if divorced from the entities that they represent. The same is true of the probablities; we need to know their method of determination.

This is well illustrated by the antecedant of Shannon's theory: the code that Morse developed in the 1830s. To increase transmission speed, Morse chose the length of his symbols for the various letters of the alphabet broadly according to the frequency (probability) with which they occur. Unlike Shannon, who did a thorough statistical analysis of English text, Morse simply estimated the relative frequencies of letters "by counting the number of types in the various compartments of a printer's type box" [6]. This shows that the Morse code was born as an abstract amalgam of two elements: pieces of lead type and the relative numbers of them in a printer's box.

In close analogy, Shannon's theory of communication considers *a source of messages* and *the probabilities with which they are chosen.* The universality of the theory rests on the multitude of things that can serve as messages: the letters of any language (with their obvious antecendant in the printer's box), the words of that language, sentences in that language, and continuous or discrete distributions in, say, a two-dimensional field of view. All such messages correspond to concrete things: type is structured lead, words stand for things,[1] and sentences for concatenations of words. Distributions are particularly important in the context of this essay. First, they establish a direct correspondence with our most immediate experiences. For every time we open our eyes, we see a distribution of coloured shapes. Such a distribution is one of the messages that nature is constantly communicating, Shannon-like, to our consciousness. Second, perceived distributions directly suggest the most fundamental ontological concept in theoretical physics: a field configuration, which in the simplest example of a scalar field can be likened to a field of variable light intensity.

On the face of it, the probabilities that, as we shall see, form such an important part in Shannon's theory, are very different from the messages, which stand for things. However, the probabilities on which Shannon based his theory (and are relevant for this essay) were all based on objective counting of relative frequencies of definite outcomes. The example of Morse proves that: he counted the numbers of different type in the printer's box. So the probabilities too have an origin in things: although they do not stand for things, they stand for proportions of things in a given environment. This is just as true of observationally determined quantum probabilities as it is for the frequencies of words in typical English or the numbers of different trees in a forest.

[1] Verbs by themselves have no meaning. In the sentence "Bit dog man" (the standard order in Irish Gaelic), we would not know what 'bit' means had we not seen canine teeth in action.

The concepts of message and probability enable one, for a definite source of N messages, to define Shannon's *information*.[2] If p_i, $i = 1, 2, ..., N$, is the relative probability of message i and $\log p_i$ is its base-2 logarithm, then the information I of the given source is

$$I = -\sum_{i}^{N} p_i \log p_i. \tag{1}$$

The minus sign makes I positive because all probabilities, which are necessarily greater than or equal zero, are less than unity (their sum being $\sum_i^N p_i = 1$), so that their logarithms are all negative.

The definition (1) is uniquely fixed by a few desirable or essential properties such as positivity and additivity; the most important is that I takes its maximum value when all the p_i are equal; the slightest deviation decreases I. If an unbiased coin, with equal probabilities $p_h = p_t = 1/2$ for heads and tails, is tossed once, the value of I is unity and defined as one *bit* of information (or uncertainty). The number of possible outcomes (messages) increases exponentially with the number N of tosses: The information I is then N and equal to the base-2 logarithm of the number M of different outcomes. For five tosses $M = 2 \times 2 \times 2 \times 2 \times 2 = 32$ and $\log_2 32 = 5$. If a coin is biased, $p_h \neq p_t$, then for a single toss I is less than one, becoming zero when only one outcome is possible. All this is rather simple and beautiful – once Shannon had the idea.

Pierce [6] carefully distinguishes the *binary digits* 0 and 1 from Shannon's information bit. There are two good reasons to do this. First, the digits 0 and 1 can serve as messages, but their probabilities of transmission may be far from equal. The information of the source will then be less than one. Second, the name binary digit for either 0 or 1 may, as John Tukey suggested, be contracted to 'bit', but one needs *equal* uncertainty associated with *two* things (which may be the two binary digits) to get *one* information bit. Pierce's distinction is useful too in helping to clarify what 'it' and 'bit' mean. Wheeler is explicit: bits are detector-elicited answers to yes or no quantum binary choices. Now an answer in quantum experiments is essentially a binary digit as defined by Pierce: for example, 0 will stand for spin down and 1 for spin up. This would be the case even if the two possible outcomes do not have equal probabilities.

The information-theoretic (1), *Shannon information*, is quite different from what most people mean by information and I call *factual information.* It is actually the *content* of Shannon's messages. It can be anything: a string of random binary digits, instructions to a bank, or the news that President Kennedy has been assassinated. If we receive a picture, we normally understand by information the distribution of colours and shapes we see when looking at it. I have already likened a distribution to a *configuration*, but the word can stand for any *structured* thing. Structure and variety are central to my critique of 'it from bit'. For we can only talk meaningfully about a thing, including a 'bit', if it has distinguishing attributes. The way that they are knit together, as in the taste, shape and colour of an apple, defines the structure of the thing. There is one metalaw of science: it cannot exist without structured things. Structured variety is the ground of being. That is what gives content to both science and life.

[2] On von Neumann's advice, Shannon also called it *entropy* by analogy with Boltzmann's entropy in statistical mechanics.

Having identified configurations as examples of Shannon messages that carry factual information, I now come to the *intrinsic semantic information* they may have. Consider the example of a *time capsule*, which I discuss in [7]. I do not mean "a container holding historical records ... deposited ... for preservation until discovery by some future age" (Webster's) but something that arises naturally. My favourite example comes from geology.[3] Two centuries ago, geologists started to establish detailed correlations between the structure of fossils and rocks found in different locations. They concluded that the correlations could only be explained by an immense age of the earth, vastly longer than the bible-deduced estimate of somewhat over 6000 years. They explained the earth's present state by a long process that had unfolded in accordance with the then known laws of nature. They discovered deep time. The geologists' discovery of physical history and the present evidence for it extends today most impressively to all branches of science, especially cosmology and genetics.

Everywhere scientists look they find records that speak with remarkable consistency of a universe which began in a very special big bang – with the geometry of space highly uniform but the matter in higgledly-piggledy thermal equilibrium – and has since evolved, creating in the process a record of what happened. For the sake of a concept to be used later, suppose one instantaneous configuration of the universe is recorded at the present cosmological epoch. Its specification (without any momentum information) is consistent with quantum mechanics and relativity.[4] In a coarse-grained form it will contain all the factual information that the geologists used to make their discovery. In fact, thanks to the stability of solids, the fossils and rocks that they used exist to this day essentially unchanged. I claim that the configuration carries intrinsic semantic information in the sense that different intelligent beings can in principle deduce *the law or process that explains the observed structure.* Support for this is the independent discovery of evolution by natural selection by Wallis and Darwin through their common reaction to the same evidence in fossils and living animals.

In summary, we must distinguish three kinds of information: Shannon's information, the uncertainty as to which message will be selected from a source; factual information, the content of such a message; and intrinsic semantic information, which distinguishes a random message, or configuration, from one that carries meaning and to some extent explains its very genesis. *All three have a firm underpinning in things.* Finally, Shannon-type message sources could not exist if the universe were not subject to laws of nature and far from thermal equilibrium.

This applies in particular to the quantum 'incarnation' of a Shannon one-bit information source: the *qubit* (quantum bit). Qubits are perfect information-theoretic bits, but they do not 'float around' in the universe ready to be put to use as message sources, any more than unbiased coins could be found in nature before humans invented them as value tokens. Qubits can be realized in many different ways [8], but all require great experimental sophistication and rely on the low entropy of the universe.

[3] Appendix A gives a very different example generated by an explicit timeless law.

[4] In relativity, fundamentally defined 'nows' are denied. However, in the actual universe cosmologists can and do define them using the distribution of matter.

4 The Status of Information

Having defined the three kinds of information, I can draw my first conclusion: information, in Shannon's sense, must have an underpinning in things. Information theory would never have got off the ground if structured things – configurations – did not exist. In a forest we can count trees and establish their relative numbers. This is just what Morse and Shannon did with type and letters. Probabilities without things are pure *no*things. It is also relevant that the *outcomes* of the experiments used to establish quantum probabilities are determined in the macroscopic classical world in essentially the same way as the outcomes of classical processes.[5]

The key point is this. If we are to speak about ontology, as opposed to efficient coding in communication channels, the most important symbol in (1) is not p for probability but i for the thing, or configuration, that has the probability p_i. Probabilities are for outcomes: what you find when you open the box. Thus, even if quantum probabilities are an integral and essential part of the world, they are meaningless in themselves. They are at best secondary essentials, not primary essentials. They must always be probabilities for *something*.

Now what does this tell us about the world and how we should conceptualize it? It is clear that quantum mechanics must be taken into account. If an experimentalist has prepared a simple two-state quantum system, a qubit, it can serve as a Shannon-type information source. The two possible outcomes are not yet factual, and at this stage the state is an inseparable amalgam of two things: outcomes and the probabilities for them. If information is understood in this strict Shannon sense, Zeilinger is right to say, in his beautiful description of teleportation experiments [9], that "the quantum state that is being teleported is nothing other than information". He then goes on to say, as an observation which he regards as very important, that "the concepts *reality* and *information* cannot be separated from each other." However, in his book Zeilinger does not define information or distinguish the kinds of information that I have so far described; by 'information' he generally seems to mean factual as opposed to Shannon information (though not in the teleportation example). I have found that other authors do make the distinction but often fail to maintain it, so that one is left trying to make out which kind of information they mean.

But whatever authors may mean by information, quantum states still give us probabilities for outcomes in the form of factual information about things. Moreover, the probabilites themselves are determined by observation of things. I therefore conclude that things are the ground of being and constitute the ontological basement. Reality creates information and *is* separate from it. Once this has been recognized, we see that, for all its importance, information theory can in no way change what has always been the starting point of science: that structured things exist, in the first place in our mind and, as a reasonable conjecture given the remarkable correlations in our mental experiences, in an external world. Moreover, the proper task of ontology is to establish *the structure of things*. To this we now turn. It brings us back to quantum yes/no experiments and the need to establish what Wheeler meant by 'it' and 'bit'.

[5] In the absence of a viable hidden-variables explanation of quantum phenomena, it does appear that quantum probabilities have a better 'birthright' than the ignorance of classical physics to appear in the expression (1) for information. However, I do not think that this affects the main thrust of my argument.

5 Wheeler's It and Bit

Wheeler explains what he means by 'it from bit' in, for example [1]. He describes an Aharonov–Bohm experiment in which an electron beam passes either side of a coil in which a magnetic flux is confined. Behind the coil is a screen on which individual electron hits are registered. The hits are found to form the characteristic fringes that arise from the quantum interference between the electron waves that pass on the two sides of the coil. When no flux is present in the coil, the fringes occupy a certain position. When a flux is present, the fringes are displaced, and from the magnitude of the displacement one can measure the strength of the magnetic field in the coil. By 'it' in the present case, Wheeler means the magnetic field and claims that it "derives its very existence entirely from discrete detector-elicited and information-theoretic answers to yes or no quantum binary choices: *bits*".

This needs some unpacking, above all of the bits. They are clearly the individual detector-elicited electron hits. The setup forces each electron to make a quantum choice as to where it will be registered, and it is from the totality of the hits that the field strength is deduced. We see that Wheeler's 'bit' is factual information. It gives the location of an electron impact. It is not a Shannon bit. Wheeler writes as if his 'bit' were one of the *binary digits*, 0 or 1, in the sense that Pierce defined them. But, in fact, it is not a single digit as could be used to record a genuine yes/no quantum outcome, say spin up or down. In this (typical) example, the record of the outcome is not one digit but a binary number of potentially infinite length because it needs to define the coordinates of the hit. To turn the hit into a yes/no (Boolean) answer, one must ask: did the electron impact within a specified area on the screen? But now infinitely many digits come into play *implicitly* through the definition of the area.

At this point, we need to ponder the very conditions that make science possible: our special place in a special universe. Above all, the universe has very low entropy. The huge range of temperatures found in different locations is sufficient evidence of that. This is why on the earth's surface we can take advantage of the solid state to perform experiments and record their outcomes, either as dots on a screen or in a computer memory. Science would be impossible without the solid state. It would also be impossible without local inertial frames of reference, in which Newton's first law holds to a good accuracy. It keeps equipment in place. The low entropy of the universe and the law of inertia are fundamental properties of the universe and both can only be understood holistically (Appendix B).

The relation of what I have just said to Wheeler's 'bits' is this. They do not exist in isolation. A 'bit' is not a single-digit 'atom of reality' as 'it from bit' implies. A dot on a screen is not the unadorned answer to a straight question. A 'bit' has no meaning except in the context of the universe.

Consider Wheeler's Aharonov–Bohm experiment. When the flux in the coil is deduced, many things must be present, including knowledge of the laws of physics, physicists to use it, and the most directly relevant information: the pattern of the interference fringes with and without flux. It is only from the difference that a conclusion can be drawn. But we also need stability of the equipment, the laboratory and its environment, which must be monitored. All this requires conditions under which records can accumulate – in brief the conditions under which time capsules can form.

Wheeler's thesis mistakes abstraction for reality. Try eating a 1 that stands for an apple. A 'bit' is merely part of the huge interconnected phenomenological world that we call the universe and interpret by science; it has no meaning separated from that complex. Just because the overall conditions of the universe enable us to observe them in carefully prepared experiments, dots on screens are no proof that at root the world consists of immaterial single-digit information. For we have no evidence that the dots could exist in the absence of the world and its special properties.

The status of Wheeler's 'it' is not controversial and requires less discussion. It is the underlying invisible world, the world of quantum fields and particles, whose existence we deduce from the correlations within the interconnected phenomenological world. Of course, quantum mechanics indicates that, in any given measurement, we can only determine half of the classical variables associated with these entities, say the position or momentum of a particle but not both at once. However, the notions of particle and field remain crucial to our interpretation of quantum phenomena. Without them, we would understand nothing. In the quantum mechanics of a system of particles the wave function is defined on the space of possible configurations of the particles. The probabilities are then determined by the configuration space and the Schrödinger wave equation. Just as in classical mechanics, laws and configurations retain their indispensable explanatory role. They are the 'its' that explain phenomena.

Crucially, even if individual quantum outcomes are unpredictable, the probabilities for them are beautifully determined by a theory based on 'its'. I noted that a Shannon bit is an amalgam of things and probabilities and that the things have the deeper ontological status. Quantum mechanics strengthens this claim: the things determine the probabilities.[6] I see nothing in Wheeler's arguments to suggest that we should reverse the mode of explanation that has so far served science so well.

This conclusion in no way settles whether nature is analog or digital; that would at the least require us to know if the 'its' are continuous or discrete.[7] However, I do think that my arguments undermine some of the more extreme forms of 'digitalism'. Abstraction creates the impression that the world is made of qubits, but humans make qubits, just as they make coins.

6 Holism and Reductionism

What are the implications of this for quantum mechanics and the nature of time and the world? Some time before he published the *Principia*, Newton wrote a paper entitled "The Laws of Motion. How solitary bodys are moved" [4]. The 'solitary' indicated that Newton would define motion relative to invisible space and time. His resulting law of inertia became the prop of reductionism; it suggests that the most essential property of a body can be established by abstracting away everything in the universe that is observable. The catch, all too often forgotten, is that an inertial frame of reference is needed to define the motion. If one asks after its origin, one is led to an account of motion in

[6]For the arguments of the following section, it is important that qubits are in stationary quantum states, for which the probabilities are defined by the *time-independent* Schrödinger equation. One has *timeless* probabilities for *possible* configurations.

[7]Nature may be both; space appears to have *three* dimensions but to be continuous.

which configurations, not bland empty space, determine local inertial motion (Appendix B). I believe this undermines reductionism.

It also calls for a definition of *the universe*. I define it [7] as a set of *possible configurations* that nature has selected for reasons, perhaps of simplicity and consistency, that we have not yet fathomed.[8] The configurations are possible *instants of time*. In this picture, there is neither a containing space nor an unfolding time. One cannot ask when or where things happen; things are their own time and place. The Greek word *onta*, from which 'ontology' derives, means both 'existing things' and 'the present'.

Such a picture may help us to understand quantum mechanics. Zeilinger [9] emphasizes that the individual quantum measurement is purely random. He comments: "This is probably the most fascinating consequence in quantum physics ... centuries of the search for causes ... lead us to a final wall. Suddenly, there is something, namely the individual quantum event, that we can no longer explain in detail." But perhaps notions of causality have too long been tied to the picture of a world evolving in space and time. Leibniz argued long ago that the world is rational and that things are judged on their merits. The criterion for existence is comparison of 'possibles', not what was set up in some conjectured past. Leibniz also argued that reality resides in configurations, not position of bodies in space [10].

Newton said of himself "I do not know what I may appear to the world, but to myself I seem to have been only a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me." Is nature like Newton? There are many pretty shells among the possible configurations. What we observe and interpret as the outcome of an individual quantum event does not reside in space and time; it is embedded in a configuration. Nature's concern will surely be the big picture. In the timeless set of *onta*, the possible configurations of the world, nature will not find the pretty shells 'now and then' but 'here and there'. And causality through time will be replaced by selection according to timeless probabilities. That is still causality but of a different kind.

I have a Leibnizian conjecture [7] that might even have pleased Newton. It is this. The set of all *onta* is the ultimate Shannon source. The semantic content of the *onta* measures their probabilities.[9] Consciousness is the communication channel from the *onta* to our experiences.

My thanks to David Deutsch for a helpful discussion, to Roberto Alamino, Harvey Brown and Nancy McGough for comments, and to Boris Barbour for the figures.

[8] As of now, the best candidates are configurations of fields defined on a manifold that carries a three-metric. In essence, these are not unlike what we see when we open eyes.

[9] This idea requires amplification! Let me just say that the time-independent Schrödinger equation determines *the most probable shapes* of molecules. It is at least possible [7] that an analogous timeless equation for the universe gives the highest probability to configurations with shapes that carry semantic information.

7 Appendix A. Maximal Variety

In the body of the essay, I describe 'time capsules' as configurations that carry intrinsic semantic content. Here I give another example. It does not suggest history, but the notion of a structured configuration is all important.

Leibniz told princesses that we live in the best of all possible worlds, but in his serious philosophy he argued that we lived in the one that is *more varied* than any possible alternative (*Monadology*, §58). Some years ago, Lee Smolin and I found a way to express this idea in a simple mathematical model. One representation is in terms of a ring of N slots (here $N = 24$) into which balls of different colours (or darkness in grey shades) can be placed (Fig. 1).

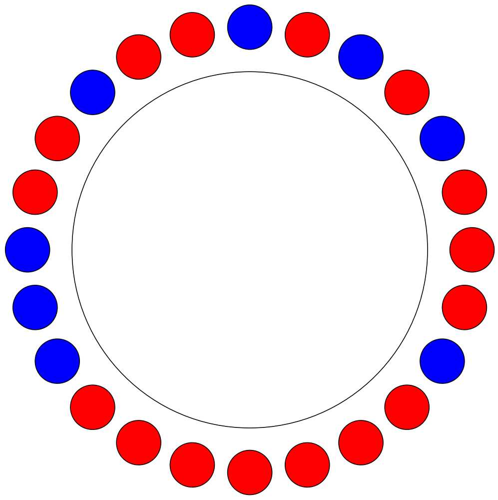

Fig. 1. The most varied two-colour (dark-light) 24-slot universe.

The diagram is maximally varied in the sense that, without pointing to a particular ball or naming colours or sense of direction, each ball is more readily identified than for any other occupation of the slots. The rule of creation is minimization of indifference (the inverse of variety). Balls are identified by their neighbourhoods: the seven-slot neighbourhood centered on ball x at noon is either the string $SDDxDSD$ or $DSDxDDS$ (left-right symmetry), where S and D are same (S) or different (D) neighbours (colour symmetry). The indifference I_{ij} of slots i and j is equal to the length (3, 5, 7, ...) of the respective strings needed to distinguish them. The total indifference of a distribution is $I = \sum_{i<j} I_{ij}$. The most varied distribution is the one for which I has its smallest value. The relative number of balls of each colour is not fixed in advance but found by the minimization of I. Figure 1 is typical of the maximal-variety configurations (in general there are 2 or 3 for each N, though for 24 Fig. 1 is the unique configuration). Interestingly, the symmetric rule of creation invariably leads to markedly asymmetric configurations. The maximally – and near-maximally – varied configurations 'proclaim their own sematics' in the sense that smart enough mathematicians could deduce the law that creates them. For more details and the results of calculations up to $N = 27$ see [11].

8 Appendix B. Best Matching

This appendix describes the motion of particles without the props of absolute space and time. Position and time are treated relationally. The basic idea – best matching – also leads to general relativity (GR) [12]. The further requiremnt of relativity of size leads to GR with a distinguished definition of simultaneity [13]. I relied on this result in Sec. 6 to argue that identifying instants of time with confgurations is not in conflict with Einstein's theory.

Consider N gravitating particles (masses m_i) in Euclidean space. For $N = 3$, Fig. 2 shows the three particles at the vertices of the triangles representing two possible relative configurations 'held in imagination' somehow relative to each other. This generates apparent displacements $\delta\mathbf{x}_i$ of particle i. Calculate (2):

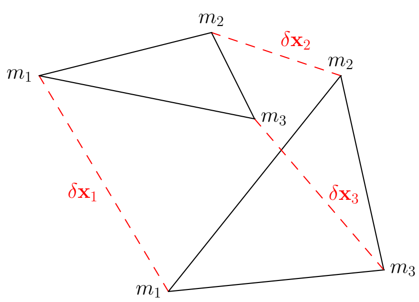

Fig. 2. A trial placing of the two triangles generates apparent displacements $\delta\mathbf{x}_i$. Minimization of the *trial action* (2) leads to the best-matched displacements.

$$\delta A_{trial} = 2\sqrt{(E - V)\sum_i \frac{m_i}{2}\delta\mathbf{x}_i \cdot \delta\mathbf{x}_i},\ V = -\sum_{i<j}\frac{m_i m_j}{r_{ij}}. \quad (2)$$

Here E is a constant. The action (2) is clearly arbitrary with no significance, but, using Euclidean translations and rotations, we can move either triangle relative to the other into the unique *best-matched* position that minimizes (2). For any two nearly identical triangles, the best-matched value of (2) defines a 'distance' between them and a metric on $\mathcal{S}$, the space of all possible relative configurations of the particles. One can then find the geodesics in $\mathcal{S}$ with respect to this intrinsically – and holistically – defined metric of the N-body universe.

It can be shown [11] that the relative motions which the particles undergo as the representative point of the system moves along the geodesic are identical to the observable relative motions of particles in the Newtonian N-body problem with total energy E and *vanishing total angular momentum*. Moreover, the increment δt of 'Newtonian' time is *derived* [14]:

$$\delta t = \sqrt{\frac{\sum_i m_i \delta\mathbf{x}_i \cdot \delta\mathbf{x}_i}{2(E - V)}}. \quad (3)$$

The combination of best matching and the geodesic requirement, which dispenses with Newton's absolute time as independent variable, leads to recovery of Newtonian behaviour of subsystems in a large N-body 'island universe'. Newton's first law, the basis of reductionism, is holistic in origin.

References

[1] J A Wheeler. Sakharov revisited: "It from Bit". *Proceedings of the First International A D Sakharov Memorial Conference on Physics, Moscow, USSR, 1991, May 27-31, ed M Man'ko, Nova Science Publishers, Commack, NY*, 1991.

[2] V Vedral. *Decoding Reality: The Universe as Quantum Information.* Oxford University Press, 2010.

[3] P C Davies and N H Gregerson (eds). *Information and the Nature of Reality.* Cambridge University Press, 2010.

[4] J Barbour. *The Discovery of Dynamics.* Oxford University Press, 2001.

[5] E Shannon and W Weaver. *The Mathematical Theory of Communication.* University of Illinois Press, Urbana and Chicago, 1963.

[6] J R Pierce. *An Introduction to Information Theory, 2nd ed.* Dover Publications, New York, 1980.

[7] J Barbour. *The End of Time.* Weidenfeld and Nicolson, London; Oxford University Press, New York, 1999.

[8] D Deutsch. It from qubit. In *Science and Ultimate Reality (Barrow, J, Davies, D, and Harper, C (eds)).* Cambridge University Press, 2003.

[9] A Zeilinger. *Dance of the Photons.* Farrar, Strauss and Giroux, New York, 2010.

[10] H G Alexander, editor. *The Leibniz–Clarke Correspondence.* Manchester University Press, Manchester, 1956.

[11] J Barbour. The deep and suggestive principles of Leibnizian philosophy (downloadable from platonia.com). *The Harvard Review of Philosophy*, 11:45–58, 2003.

[12] J Barbour. Dynamics of pure shape, relativity and the problem of time (arXiv/gr-qc/0309089). *Lect. Notes Phys.*, 633:15–35, 2003, gr-qc/0309089.

[13] E Anderson, J Barbour, B Z Foster, B Kelleher, and N Ó Murchadha. The physical gravitational degrees of freedom. *Class. Quantum Grav.*, 22:1795–1802, 2005, gr-qc/0407104.

[14] J Barbour. The nature of time (arXiv:0903.3489), 2009, arXiv:0903.3489 [gr-qc]. Winner of first juried prize essay of The Foundational Questions Institute (fqxi.org).