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Nanoscale Technology: A Two-Sided Challenge for Interpretations of Quantum Mechanics

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Abstract. In this contribution I consider the consequences of using quantum mechanics in nanoscale technology. I argue that this use leads to a problem that poses a two-sided challenge for interpretations of quantum mechanics. Firstly I present the problem: engineers typically ascribe technical functions to artifacts; function ascriptions imply particular physical descriptions of artifacts, and quantum mechanics sometimes fails to reproduce these descriptions. This problem may be solved by adopting an interpretation of quantum mechanics. An interpretation turns quantum mechanics into a theory that gives richer physical descriptions and that may reproduce the physical descriptions implied by function ascriptions. It can be shown, however, that not all interpretations fulfill this promise. Secondly I argue that these results amount to a two-sided challenge. It challenges philosophers of physics to provide an interpretation that gives nano-engineers rich enough quantum-mechanical descriptions to ascribe functions to artifacts. And it challenges engineers to help philosophers of physics with selecting tenable interpretations. Philosophers of physics are in need of tests for judging the different existing interpretations, and nano-engineers can provide such tests by requiring that interpretations should reproduce the function ascriptions to the artifacts they design. A nanoscale technology example I consider is quantum teleportation.

Introduction

Quantum mechanics has found its way to technology. Nuclear technology and laser technology are well-established examples, quantum cryptography and quantum computer technology are emerging ones. Nanoscale technology, when realized, will increase the use of quantum mechanics in technology. Quantum mechanics is the theory that describes matter on the atomic level. So, if nano-engineers are to build their universal assemblers that "will let us place atoms in almost any reasonable arrangement",[1] then quantum mechanics is the theory they apply.

Already in his seminal work Drexler reviewed the consequences of this use of quantum mechanics in nanoscale technology. His message appears to be that these consequences can be brushed aside. Drexler considered, for instance, the question of whether the uncertainty principle of quantum mechanics "makes molecular machines unworkable", and concluded that one "needn't study quantum mechanics" to come up with a negative answer: the biological cell "demonstrates that molecular machines work". Drexler also mentioned the perceived strangeness of quantum mechanics and the revolution it caused in our knowledge about matter. But again he reassured us that our knowledge about "the world of living things and the machines we build" will not be upended any further: future quantum-mechanical oddities and novelties will only occur under extreme circumstances engineers are never faced with.[2]

In this contribution I also consider the consequences of using quantum mechanics in nanoscale technology. In contrast to Drexler, I argue that this use leads to a problem that should not be brushed aside. This problem is that quantum mechanics cannot always accommodate a rather essential element in engineering descriptions of technical artifacts, namely, that these artifacts have technical functions. This problem should be solved since it seems obvious that engineers also will ascribe technical functions to the nanoscale artifacts they are to design. Moreover – and more positively – this problem poses a two-sided challenge for the philosophy of quantum mechanics that, when taken up, may lead to progress in this field.

More specifically I consider the quantum-mechanical description of nanoscale artifacts and argue that this description can fail to accommodate function ascriptions to those artifacts. I show that this omission is due to a general problem of quantum mechanics, namely, that it provides a rather sparse description of the world: quantum mechanics can easily temporarily deny an atom a familiar physical property such as position, velocity or energy. Then I argue that quantum-mechanical descriptions of artifacts may accommodate function ascriptions if one adopts an *interpretation* of quantum mechanics. Such interpretations have been developed in the philosophy of physics and are meant as solutions to the just-mentioned general problem by turning quantum mechanics into a theory that gives a richer description of the world. It can be shown, however, that not all interpretations fulfill this promise of accommodating functions. This is the first side of the challenge that is posed by the use of quantum mechanics in nanoscale technology. It challenges philosophers of physics to provide an interpretation of quantum mechanics that gives nano-engineers the means to ascribe functions to artifacts. Finally, I argue that in response, nano-engineers may also help philosophers of physics. Nowadays there exist many competing interpretations of quantum mechanics, and philosophers of physics are in need of clear tests for judging them. I propose that nano-engineers can provide such tests by requiring that interpretations of quantum mechanics should accommodate the functions they ascribe to the nanoscale artifacts they will design. And this is the second side of the challenge. It challenges nano-engineers to come up with functional descriptions of artifacts that enable philosophers of physics to decide which of the existing interpretations are tenable.

The plan for this contribution is as follows. In section 1, I consider functional descriptions of artifacts and state how a physical theory can accommodate them. Quantum mechanics and its interpretations are introduced in a colloquial way in section 2. In section 3, I show how quantum mechanics is capable of accommodating the ascription of technical functions to a specific class of artifacts, namely, measurement devices. The argument that quantum mechanics can also fail to accommodate function ascriptions, is given in sections 4 and 5. For this argument I consider other artifacts, namely, decoders that are part of a scheme called 'quantum teleportation'. In section 6, I discuss how nano-engineers and philosophers of physics meet in attempts to overcome this problem.

Although I am happy with arguing that nano-engineers and philosophers of physics may benefit from one another's work, it also confronts me with the problem of addressing two audiences. This contribution is therefore part of a pair that also includes a more quantum-mechanical paper. Here I introduce the reader to quantum mechanics in a colloquial fashion and stripped of mathematical niceties. The discussion of measurement devices and teleportation decoders is likewise rather informal. In the complementary paper the quantum-mechanical details are given by means of the usual theoretical language (Vermaas 2004). That paper contains the proofs of the different claims which are only presented here.

1. Technical Functions

If a material object is taken not only as a physical object but also as a technical artifact,[3] its description becomes substantially richer. The description of a material object 'qua' physical object makes use of physical and chemical concepts such as geometrical dimensions, configuration, mass, types of matter, and so on. But if that object is taken as an artifact as well, intentional concepts enter the description. The object was designed and made by specific persons, and the object is meant to be used by people for achieving goals. An artifact has a technical function and may consist of components that have subfunctions. Technical artifacts are thus described by both physicochemical *and* intentional concepts and can be said to have a 'dual nature'[4] in contrast to purely material objects that have merely one physical nature. These physical and intentional descriptions are not independent from one another. If a technical artifact is described intentionally as an object with the technical function of drilling holes, it clearly can't be described physically as a lump of sugar. Hence, the intentional description of a technical artifact typically imposes constraints on its physical description.

In this contribution I focus on the description of nanoscale artifacts as material objects that are ascribed technical functions. I take the position that the constraints these function ascriptions impose on the physical descriptions of artifacts can be captured by conditional statements about physical states of affairs. For everyday artifacts, these constraints are met: everyday artifacts are described by classical physics and classical physics provides for physical descriptions of artifacts that are rich enough for reproducing the mentioned conditionals. But for nanoscale artifacts described by quantum mechanics, things are different. Quantum-mechanical descriptions of nanoscale artifacts need not reproduce the physical conditionals and in that way fail to accommodate function ascriptions. But before being able to argue for this, I firstly consider functional descriptions of artifacts in more detail, and then introduce quantum mechanics in the next section.

Technical artifacts can be ascribed technical functions. A light bulb has the function of emitting light and a lawn mower has the function of cutting grass. There is, however, no consensus about what such function ascriptions mean. Philosophers have defended a number of positions. Some authors relate functions mainly to the *intentions* of agents. Searle, for instance, analyses function ascriptions in terms of the purposes agents impose and the suppositions they make: if an agent ascribes a function f to an artifact x, this implies that (*i*) the agent takes x as part of a larger system on which s/he imposes certain goals, and that (*ii*) the agent supposes that x can cause or result in f-ing in virtue of its physical makeup (Searle 1995). So, if an agent ascribes to a bulb the function of emitting light, s/he imposes, say, the goal of illumination to a lamp of which the bulb is a part, and s/he supposes that the bulb can emit light by its physical structure. Neander takes the position that "the function of an artifact is the purpose or end for which it is designed, made, or (minimally) put in place or retained by an agent" (Neander 1991, p. 462). Hence, ascribing to a lawn mower the function of cutting grass means that it was designed by engineers for cutting grass, or that a gardener kept it in a shed for this end. Other philosophers relate functions of artifacts not to the intentions of agents but to the *physical roles* of those artifacts in larger systems. Cummins, for instance, takes the ascription of a function f to an artifact x part of a larger system as implying that (*i*) in that larger system x actually has the capacity of f-ing, and that (*ii*) this capacity of x explains in part that the larger system has some other capacity (Cummins 1975). So, ascribing to the bulb in a lamp the function of emitting light means now that the bulb has the physical capacity to emit light and that this explains in part why the lamp has the physical capacity to illuminate. A third group of philosophers sees an analogy between technical functions and mathematical functions. They take function ascriptions to artifacts as ascriptions of *input-output relations*: saying that the lawn mower has the function of cutting grass means that it transforms non-cut grass into cut grass.[5]

This is not the place to settle the debate between the different positions on what it means to ascribe functions. I therefore adopt a particular position that was argued for by Houkes and Vermaas (2004). Firstly, I assume that the ascription of a technical function f to an artifact x implies that x has a corresponding physical capacity (categorical or dispositional).[6] The light bulb has the capacity to emit light when an appropriate electrical current is running through it, and the mower can cut grass when it is brought in an appropriate state. Secondly, I assume that the ascription of a physical capacity to an artifact x implies, in turn, the ascription of conditional physical relations to x: if certain physical circumstances C pertain, then the artifact will exhibit certain physical results R.[7] These two suppositions lead to the following position. If the function f is ascribed to an artifact x, then a conditional relation is ascribed to x that is given by:

$$f\colon C \Rightarrow R,$$

where C and R refer to physical states of affairs. The descriptions of C and R need not necessarily be in terms of physical properties of the artifact x itself. For the bulb C can be described as an electrical current flowing through the bulb, and R as the bulb emitting light. But for the mower R are cuts in blades of grass. This position coheres with the analyses that relate technical functions to physical roles and to input-output relations; it need not cohere with analyses that relate functions to intentions of agents.[8]

On this position a function ascription to an artifact puts constraints on the physical description of the artifact: this physical description should accommodate the physical conditional $C \Rightarrow R$ implied by the function ascriptions.

2. Quantum Mechanics and its Interpretations

Quantum mechanics is the theory developed in the beginning of the twentieth century by people such as Bohr, Heisenberg and Schrödinger to describe the physics of atoms and elementary particles. In that period classical physical theories – Newtonian mechanics, electrodynamics, and so on – were found not to adequately describe these particles and thus lost their status as universally applicable theories. For some time classical and quantum theories coexisted peacefully as two ‘partially universal’ theories. Bohr took quantum mechanics as the theory that describes the atomic realm and Newtonian physics as the one that covers the everyday realm of macroscopic objects. Nowadays, however, quantum mechanics and its successors have taken over and are the universal and fundamental theories that reveal the physics of elementary particles and of all objects – macroscopic or not – made up of these particles. Classical theories are consequently seen as merely useful tools: they provide descriptions of macroscopic objects that approximate the correct quantum-mechanical descriptions.

Despite this success, quantum mechanics is also a rather problematic theory. Quantum mechanics describes physical objects in a manner that substantially deviates in two ways from the descriptions provided by the more familiar classical theories. Firstly, it does not systematically ascribe properties such as ‘position’, ‘velocity’ and ‘energy’ to objects, whereas classical theories do; quantum mechanics systematically describes the properties only of measurement devices (and then only those properties that correspond to the outcomes these devices are supposed to display). Secondly, there is in quantum mechanics a fundamental distinction between the description of measurements and of processes that do not count as measurements, whereas this distinction is absent in classical theories. These differences had the effect that physicists and philosophers of physics have tried and are still trying to reformulate quantum mechanics in such a way that the gap between quantum mechanics and classical physics diminishes. These reformulations are called interpretations of quantum mechanics.

Before I illustrate this and in order to further prepare the ground for discussing the quantum-mechanical descriptions of nanoscale artifacts, I expand a bit on quantum mechanics in the formulation by von Neumann (1955).

Quantum mechanics describes the physics of a system x by assigning a state to that system. This state determines some physical properties of the system and, probabilistically, all outcomes of measurements performed on the system. The state may be represented by a 'wave function' ψ and generates a probability $p(\psi,A,a)$ for each physical magnitude A pertaining to x and each value a that this magnitude may take. Examples of magnitude are the position of x, the velocity of x, or its energy. The meaning of the probability $p(\psi,A,a)$ is given by two rules:

Property Rule:
If and only if $p(\psi,A,a) = 1$, then x has the property that magnitude A has value a.

Measurement Outcome Rule:
If magnitude A is measured on x, then the outcome is a with probability $p(\psi,A,a)$.

Consider now a system with a specific state ψ. If one calculates the probabilities $p(\psi,A,a)$ for this system, one obtains the following. For some magnitudes A of the system the probabilities $p(\psi,A,a)$ are equal to 1 or 0. That is, for each of these magnitudes there exists one value a' for which $p(\psi,A,a')$ is equal to 1, and for all other values the probabilities $p(\psi,A,a)$ are equal to 0. But there are also magnitudes A of the system for which it holds that the probabilities $p(\psi,A,a)$ are smaller than 1 for all the possible values a. This fact does not constrain the effectiveness of quantum mechanics to generate predictions about measurements: the Measurement Outcome Rule produces such predictions regardless of whether one measures magnitudes A for which the probabilities $p(\psi,A,a)$ are equal to 1 or 0, or all smaller than 1. But this fact does constrain the effectiveness to ascribe properties to systems: the Property Rule only ascribes properties associated with magnitudes A for which the probabilities $p(\psi,A,a)$ are equal to 1 or 0 – this rule then ascribes the property 'A has value a'' – but it does not ascribe properties associated with magnitudes A for which the probabilities $p(\psi,A,a)$ are all smaller than 1 – in this case the properties 'A has value a' are for all values a not ascribed. If such a magnitude is position or energy, and that may very well be the case, then the system has (temporarily) not a definite location in space, or no specific energy. This amounts to the first difference between quantum mechanics and classical physics. According to classical physics, systems usually have properties such as 'the position has value p' and 'the energy is e'.

The state ψ of a system x evolves in time, and quantum mechanics gives again two rules for this evolution. The first rule is deterministic and applies when no measurements are performed on x: in this case the state ψ of x evolves with certainty to a later state ψ^*. The second is the notorious 'collapse of the wave function'-rule. This rule is a probabilistic one and holds when measurements are performed. Assume that x has the state ψ and that the magnitude A is measured. The outcome is then value a with probability $p(\psi,A,a)$. The collapse rule now states that if the outcome is indeed value a, then the state of x becomes a new state ϕ for which holds that $p(\phi,A,a)$ is equal to 1.[9] Hence, the original state ψ changed with probability $p(\psi,A,a)$ to this new state ϕ. The rules for state evolution, given more compactly:

Deterministic Evolution Rule:
If no measurement is performed on x, then the state ψ of x evolves deterministically to a later state ψ^*.

Collapse Evolution Rule:
If magnitude A is measured on x and the outcome is a, then the state ψ of x changes with probability $p(\psi,A,a)$ to a state ϕ for which holds that $p(\phi,A,a) = 1$.

The fact that there are in quantum mechanics distinct rules for the evolution of the states of systems during measurement amounts to the second difference with classical physics. Classical theories treat measurements and non-measurement processes alike; they usually give one uniform rule for the evolution of states.

Among philosophers of physics there have been extensive debates about whether or not quantum mechanics is an acceptable physical theory. May a theory be silent about whether systems possess key properties such as 'the position has value p' and 'the energy is e'? And may a theory distinguish between the description of the evolution of the states of systems during measurements and during non-measurement processes? This second question is even more complicated since quantum mechanics does not give a criterion for distinguishing measurements from other processes. The concept of a measurement is a primitive one in quantum mechanics, meaning that the characterization of measurements has to come from outside quantum mechanics. A number of options are available. A first well-known one is that conscious observers make the difference: whenever agents consciously observe the properties of systems, a measurement takes place. A second option is that large macroscopic systems count as measurement devices and that interactions with those devices are measurements. And thirdly, one can take the position that in practice experimenters just know when measurements take place. All these options have their disadvantages. The first makes 'consciousness' a central notion in the formulation of quantum mechanics – a conclusion that makes quantum mechanics even more odd compared to other physical theories. The second is less than strict. The distinction between atomic and macroscopic systems is a gradual one. And throughout the years it has been shown that larger and larger systems can evolve by means of the Deterministic Evolution Rule proving that (more) macroscopically sized systems need not always be measurement devices. It was recently shown, for instance, that the states of molecules with a mass equal to approximately 1632 times the mass of a single hydrogen atom can evolve by the Deterministic Evolution Rule.[10] Also, nanoscale artifacts are nice examples of this development: the quantum dots that are currently constructed and studied are not single atoms but are described by the Deterministic Evolution Rule. Finally, the practical way out seems to imply that experimenters have a criterion but are unable to articulate it.

An *interpretation* of quantum mechanics is now meant to turn quantum mechanics into a more acceptable theory. For instance, an interpretation provides rules that ascribe more properties to systems than does the Property Rule. This may seem a simple task: just take a rule that assigns values to all the magnitudes A pertaining to a system. However, rules that ascribe more properties to systems than does the Property Rule can lead to inconsistencies, as was proved by Kochen and Specker (1967). An interpretation thus has to find a balance: it has to ascribe enough additional properties to systems for turning quantum-mechanical descriptions into sufficiently informative ones, but avoid ascribing too many properties in order to prevent inconsistencies. An interpretation, moreover, provides a single rule for the evolution of states in order to prevent a fundamental distinction between measurements and other processes.

Physicists and philosophers of physics have developed in the last century a number of such interpretations. Well-known examples are 'Bohmian mechanics' and Everett's 'relative state interpretation' (Bohm 1952, Everett 1957); more recent ones are modal interpretations.[11] There are thus many ways in which quantum mechanics can be made more acceptable.

3. Measurement Devices

Let us now consider artifacts that are described by quantum mechanics. Can quantum mechanics itself reproduce the physical conditionals $C \Rightarrow R$ implied by the functions ascribed to these artifacts? Quantum mechanics itself already provides a class of such artifacts: the measurement devices to which it grants such an important status. The conditional relations implied by function ascriptions to measurement devices can indeed be reproduced by quantum mechanics itself. But a more detailed analysis reveals problems.

By the Measurement Outcome Rule the function f_m of a measurement device m is to measure a magnitude A on a system x with state ψ_x, and to reveal an outcome a with probability $p(\psi_x,A,a)$. The outcome is to be displayed by the device as a pointer pointing to the value a on some scale, or as a digit on a screen. Usually an 'outcome magnitude' R is associated with these outcomes; the measurement device then displays the outcome a if and only if it possesses the property 'R has value a'. The physical conditional implied by this function ascription can thus be stated as:

f_m: state ψ_x of $x \Rightarrow$ device property 'R has value a' with probability $p(\psi_x,A,a)$.

This conditional can be reproduced if measurements are described in more detail (a reader less interested in details may skip the remainder of this section). The standard toy-model of a measurement of a magnitude A of a system x by means of a measurement device m is as follows. The system x has its state ψ_x and the device has a particular initial state ψ_m. Together these two systems have a joint state Ψ_{xm}. The measurement interaction takes place and by the Deterministic Evolution Rule the joint state becomes Ψ_{xm}*. If this would be the whole story, then there is a problem. If one calculates the probability $p(\Psi_{xm}*,R,a)$ for the outcome magnitude R, then one obtains that this is equal to $p(\psi_x,A,a)$. This result makes sense because the measurement device is required to have the property 'R has value a' with probability $p(\psi_x,A,a)$. But the consequence is that the device in general does not have the property 'R has value a'; $p(\psi_x,A,a)$ need not be equal to 1. It thus appears that the device does not display this property 'R has value a' as an outcome. Fortunately this is not the end of the story. Since we are dealing with a measurement, the state of the system x has to change by the Collapse Evolution Rule. The state of x has to become ϕ_x with probability $p(\psi_x,A,a)$ and for this new state holds that $p(\phi_x,A,a)$ is equal to 1. Through this change the joint state of x and the device changes as well: it changes with probability $p(\psi_x,A,a)$ to a state Φ_{xm} for which holds that $p(\Phi_{xm},R,a)$ is equal to 1. Hence, by the Property Rule, the measurement device does have the property 'R has value a' and thus possesses the outcome after all. The above conditional implied by the function ascription to the measurement device is thus reproduced.

In models for measurements that are slightly more realistic than the one described, it may, however, become difficult to reproduce this physical conditional for measurement devices. Consider, for instance, a model in which the measurement device is described as consisting of components rather than of one monolithic object. Say, the device m consists of a pointer p and a mechanism q. The measurement interaction can then be split into firstly an interaction between the system x and the mechanism q, and secondly an interaction between the mechanism q and the pointer p. Let the first interaction be similar to a measurement interaction but assume that the 'outcome' magnitude R_q of the mechanism cannot be observed by humans (say, the properties 'R_q has value a' are too small to be detected). Let the second interaction also be similar to a measurement interaction and assume that it magnifies the values of R_q to values of a magnitude R_p of the pointer that can be observed. A measurement by means of a Geiger counter is one that satisfies this scheme: if the counter interacts with an incoming particle, this particle first produces a small electrical current and this current is then transformed into audible beeps. The function ascriptions to p and q imply the conditionals:

f_q: state ψ_x of $x \Rightarrow$ mechanism property 'R_q has value a' with probability $p(\psi_x,A,a)$,

f_p: mechanism property 'R_q has value a' $\Rightarrow$ pointer property 'R_p has value a'.

The measurement interaction between the system x and the measurement device p+q consists now of the sequence of interactions between x and q and between q and p. And on the basis of this one can argue that the collapse of the state of x takes place only after q and p have interacted. Hence, during the period in which the interaction between x and q has ended but the interaction between q and p has not ended yet, the joint state of x and q is a state Ψ_{xq}^* for which holds that $p(\Psi_{xq}^*,R_q,a)$ is equal to $p(\psi_x,A,a)$. And because $p(\psi_x,A,a)$ need not be equal to 1, it follows that during that period the mechanism q does not have the property 'R_q has value a'. Hence, during that period the conditional implied by the function ascribed to q is not reproduced by quantum mechanics. Only once the interaction between q and p has also ended and the states have changed by the Collapse Evolution Rule, q will obtain the property 'R_q has value a'. And only then one can conclude that the conditional implied by q's function is reproduced.

The upshot of all this is that the conditionals implied by function ascriptions to measurement devices can be reproduced by quantum mechanics because the states of systems collapse in quantum mechanics. But if this collapse is postponed a bit, then those conditionals may (temporarily) not be reproduced by quantum mechanics. In the next two sections I consider other artifacts described by quantum mechanics. I argue that in the quantum-mechanical descriptions of these artifacts, collapses of states need not occur, and that quantum mechanics then cannot reproduce the conditionals implied by function ascriptions.

4. Decoders in Quantum Teleportation

Other artifacts that are described quantum-mechanically are the systems realized or envisaged as part of the emerging fields of quantum cryptography, quantum teleportation and quantum computation.[12] Examples are quantum dots in quantum computers and the various components – decoders, encoders, channels, and so on, that is, part of schemes for sending and encrypting information. In this section I consider one of these artifacts, namely, the decoder that is part of *quantum teleportation*, a scheme for transferring the quantum-mechanical state ψ of one particle via an ordinary digital channel to another (distant) particle. In the scheme proposed by Bennett and collaborators, a decoder interacts with the first particle and produces the digital signal that is sent to the other particle (Bennett *et al.* 1993). I here focus on the function that is ascribed to this decoder.

The quantum teleportation scheme works as follows (see figure 1).[13] Particle 1 initially has the quantum state ψ. This particle hits a decoder d at position A where a girl called Alice is located. At the same time a second particle 2 also arrives at the decoder, and this second particle originates from a source K. This source has emitted a pair of particles, of which particle 2 is one. The other particle – particle 3 – is sent to a second position B, where Bob is located. This pair of particles 2 and 3 is emitted in a special state, called an 'Einstein, Podolsky, Rosen (EPR)-state'. Moreover, Alice can send digital signals to Bob via a channel c and Bob has an 'encoder'-device e that can transform the state of particle 3.

The procedure that is followed is that Alice performs a measurement with her decoder d on the joint system consisting of the particles 1 and 2. She measures a specific magnitude G and records the outcome. In the standard case this measurement has four possible outcomes g_1 to g_4, and quantum mechanics predicts that all these outcomes occur with equal probability 0.25. Then she sends this outcome digitally to Bob via the channel c. Bob receives it and performs a quantum-mechanical transformation with his encoder *e* on the state of particle 3; for each outcome g_1, g_2, g_3, and g_4 he has a different transformation. After this transformation particle 3 has exactly the state ψ that particle 1 originally had. This result may seem trivial. It may seem that Bob knows what state particle 1 initially had once he receives Alice's signal. It is then simple for Bob to transform the state of particle 3 into that same state. However, quantum teleportation is not trivial since Alice and Bob neither can reconstruct the precise state of particle 1, nor need to do so. Ignorant of ψ they simply follow the procedure and manage to transfer this state to particle 3. Moreover, they manage to do so with a finite number of digital bits (two bits in the standard case) whereas if Alice had known the state ψ and wanted to inform Bob about it, she had to send an infinite number of bits.

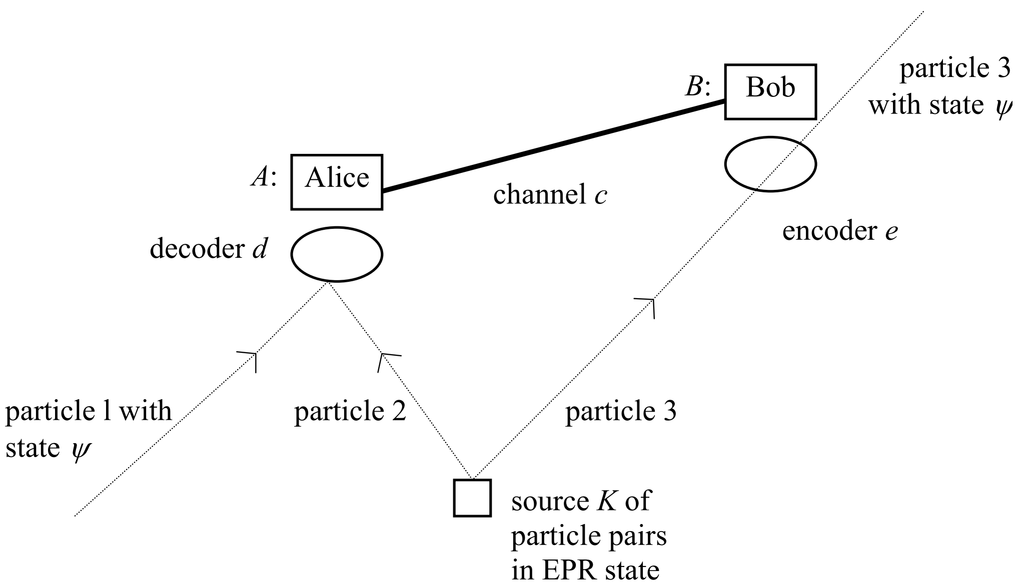

Figure 1. Quantum Teleportation

Let's now consider the decoder *d* in this scheme. It has the function f_d to decode the quantum-mechanical state ψ of particle 1 into a signal that Alice can send to Bob. This signal is the outcome of a measurement of magnitude *G* on the joint system consisting of the particles 1 and 2, and may take the values g_i, where *i* runs from 1 to 4. Let Ψ_{12} denote the state of the joint system 'particles 1+2'. The conditional $C \Rightarrow R$ implied by the function of this decoder *d*, can then be written as:

f_d: state Ψ_{12} of 1+2 $\Rightarrow$ decoder property 'R has value g_i' with probability 0.25,

where *R* is the observable outcome of the decoder.

The quantum-mechanical description of the decoder can reproduce this conditional without problems. Since the decoder is a taken as a measurement device, it follows that its state collapses after its interaction with particles 1 and 2, and that the decoder then indeed acquires a property 'R has value g_i' with probability 0.25.

5. Decoders in Nanoscale Quantum Teleportation

The teleportation scheme as presented above and discussed in the literature seems fine and is of technological significance. To be sure, it will be a challenge to design a system that allows particles 2 and 3 to arrive at the decoder and encoder without being disturbed by outside interferences. But once that is achieved, quantum-mechanical states ψ can be sent via a finite number of digital signals – an impressive case of data-reduction. But the scheme can also be criticized. And if this criticism is taken seriously, one can argue that the conditional implied by the function ascription to the decoder may fail to be reproduced by quantum mechanics.

Let us start with the criticism which is prepared by two points. The first is an empirical one and concerns the incorporation of Alice and Bob in the scheme. Authors have proposed experimental set-ups to actually perform teleportation and have to some extent shown that teleportation is possible.[14] But these set-ups do not always incorporate human agents who take the roles of Alice and Bob. In these there are, for instance, no 'Alices' included who determine the outcome that is displayed by the decoder and who feed this outcome into a channel. Instead the decoder is directly connected to this channel. It thus seems that Alice and Bob can be removed from the scheme, and it seems that the signaling between the decoder and the encoder via the channel can be modeled as successive physical interactions between the decoder, the channel, and the encoder. This scheme would have the further advantage that all systems involved in quantum teleportation can be described quantum-mechanically, which is consistent with the fact that quantum mechanics is a universally valid theory. (In the teleportation scheme discussed in the literature, Alice, Bob and the channel *c* are kept outside the quantum-mechanical description, which seems to bring us back to the times of Bohr).

The second point makes use, in part, of the prospects of nanoscale technology and challenges the assumption that the interaction between the decoder and particles 1 and 2 needs to be taken as a measurement. Quantum mechanics itself provides no criterion for distinguishing measurements from other interactions. It was shown in section 2 that such a distinction has to come from outside quantum mechanics and that a number of options are available.

On the basis of these two points, it can now be challenged whether on any of these options the decoder really has to be taken as a measurement device. The first option was that conscious observers make the difference: when a conscious agent observes a system it counts as a measurement. If one now accepts that quantum teleportation need not incorporate Alice and Bob, the decoder interaction with the particles is by this first criterion not a measurement implying that the decoder it not a measurement device. The second option was that large macroscopic systems count as measurement devices. The equipments used for the decoders in the mentioned experiments probably have macroscopic dimensions and thus are measurement devices by this second criterion. But this need not always be the case, especially from the perspective of nanoscale technology. Imagine that teleportation will become commercially available and that one can send one's quantum-mechanical states from, say, Darmstadt in Germany, to Columbia in South Carolina. Initially it may be something special, instantiated in huge expensive machinery and operated by skillful staff that sends and receives the signals 'manually'. The staff then takes the roles of Alice and Bob. But as nanoscale technology advances and competition for market share increases, teleport companies may make the staff redundant and miniaturize the machinery. One then has fully automated 'on-line' teleportation links: glass fibers with nanoscale decoders and encoders on their tips that automatically teleport incoming states. If such a scenario comes true, the decoder becomes a nanoscopic device and is thus not a measurement device on the 'macroscopic dimensions'-criterion. Moreover, the decoder may also become a kind of device that experimenters typically do not use as measurement devices. Indeed, the decoder may no longer contain a pointer or a display, but can be a minuscule component attached to the glass fiber. Hence, also by the 'determined by experimenters'-criterion the decoder now ceases to be a measurement device.

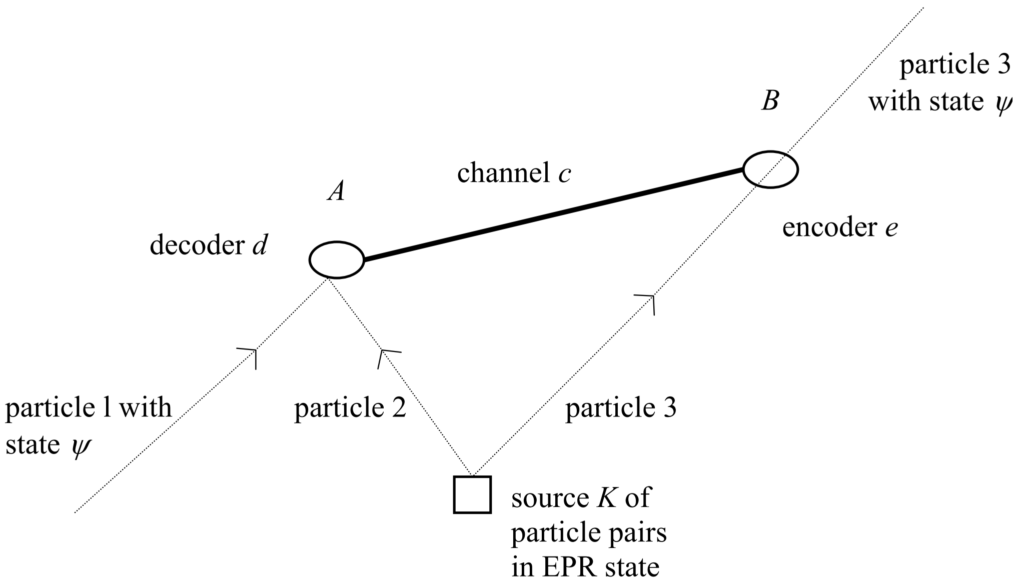

Figure 2. Nanoscale Quantum Teleportation

The upshot of this criticism is that quantum teleportation may become a nanoscale 'de-agentized' procedure in which the decoder is not a measurement device (see figure 2). All systems part of this scheme can then be described quantum-mechanically and the relevant states all evolve only with the Deterministic Evolution Rule. Since there are no measurements involved in the scheme, states do not change by the Collapse Evolution Rule. It can be proved that this new scheme still transfers the initial state ψ of particle 1 to particle 3 (Vermaas 2004), which supports the position that neither the presence of Alice and Bob, nor the assumption that the decoder is a measurement device are necessary ingredients of quantum teleportation.

But does the quantum-mechanical description of this nanoscale quantum teleportation scheme still reproduce the conditional $C \Rightarrow R$ implied by the function ascription to the decoder? The answer is negative. The decoder now has the function f_d to decode the state Ψ_{12} of particles 1 and 2 into a signal that is sent through channel c to the encoder. Let the signals correspond to the properties 'S has value g_i', $i = 1, 2, \ldots$, where S is the 'signal magnitude' of the channel c. The conditional implied by this function can then be written as:

f_d: state Ψ_{12} of 1+2 $\Rightarrow$ channel signal 'S has value g_i' with probability 0.25.

A quantum-mechanical description of the channel c reveals, however, that it never possesses one of the properties 'S has value g_i': the channel acquires a state ψ_c for which holds that $p(\psi_c,S,g_i)$ is not equal to 1 (the probability $p(\psi_c,S,g_i)$ is equal to $p(\Psi_{12},G,g_i)$, which always has the value 0.25). Hence, by the Property Rule, the channel does not possess one of the channel signals 'S has value g_i'. The above conditional is thus not reproduced by quantum mechanics. So, to conclude, descriptions of technical artifacts by quantum mechanics sometimes fail to accommodate the technical functions that (nano-)engineers ascribe to those artifacts.

6. A 'Technical Descriptions' Criterion for Interpretations

One may now try to correct this failure in the quantum-mechanical descriptions of artifacts by adopting an interpretation of quantum mechanics. An interpretation ascribes more properties to systems than quantum mechanics itself. So, possibly an interpretation does reproduce the conditionals $C \Rightarrow R$ implied by function ascriptions. This strategy may work in the case of the detector of our nanoscale quantum teleportation scheme: many interpretations do ascribe the signals 'S has value g_i' to the channel.[15] By providing nano-engineers with rich enough interpretations philosophers of physics may thus help these engineers with the accommodation of function ascriptions to artifacts described by quantum mechanics.

However, this strategy confronts one with another problem, namely the problem of which interpretation to adopt. As was said at the end of section 2, there are currently a number of interpretations available and many of them ascribe the signal. The existence of all these interpretations has now transformed the problem of interpreting quantum mechanics partly into a *selection problem*: instead of just finding an interpretation for quantum mechanics, one now also has to judge which of the existing interpretations is the best or, more humbly, which are the tenable ones. I will show in this section that this selection is currently difficult because philosophers of physics lack clear, generally accepted, and discriminating criteria for judging interpretations (Vermaas 2003). Nano-engineers can, of course, take the easy way out of this second problem by assuming that it is sufficient to know that there exists an interpretation by which quantum mechanics can accommodate function ascriptions; the problem of selecting interpretations is then moved back to the philosophy of physics, where the problem was caused in the first place. I wish to argue that philosophers of physics can be helped in solving their problem if this strict division of labor is overcome.

Philosophers of physics have two clear and accepted criteria available for considering the selection problem: a tenable interpretation should be *consistent* and *empirically adequate*. The first criterion indeed succeeded to remove some interpretations: the mentioned proof by Kochen and Specker showed that interpretations that ascribe too many properties can be inconsistent. But this criterion has done its job and does not discriminate any further. One may assume that the main interpretations that are now available are all consistent. The second criterion appears stronger, but is in fact also not very effective in turning down interpretations. An interpretation of quantum mechanics ideally generates exactly the same empirical predictions as quantum mechanics itself. As stated above, interpretations are meant to turn quantum mechanics into a more acceptable theory; they are not meant to change the empirical content of quantum mechanics. A consequence of this is that empirical tests in principle cannot differentiate between tenable and untenable interpretation.

Philosophers of physics also apply more discriminating criteria to interpretations. But these criteria are not (yet) generally accepted. An extensively discussed criterion in physics is the requirement that interpretations of quantum mechanics should yield '*local*' and '*Lorentz-covariant*' descriptions of reality in order to maintain consistency with Einstein's theory of relativity. This criterion, however, does not help selecting tenable interpretations either. It can be formulated in a strong and straightforward way, but then it seems that no interpretation satisfies it. Weaker formulations are possible and these allow some interpretations to survive and others not. But this moves the game of selecting interpretations towards a debate on the right way of weakening the criterion. This then reveals that the criterion doesn't yet have a clear and generally accepted form. There are other more specific criteria proposed in the philosophy of physics literature. Clifton, for instance, lists five "desiderata" for modal interpretations (Clifton 1996). These range from an elusive desideratum that the set of ascribed properties should be 'metaphysically' tenable, to a more tangible one that modal interpretations should provide for a dynamics of these properties. Cushing and Bowman speak of possible conceptual advantages of Bohmian mechanics over quantum mechanics itself, since the former may provide better means to connect quantum mechanics to other theories such as chaos theory and classical mechanics (Cushing and Bowman 1999). These criteria are to some extent clear and may be discriminating. But their effectiveness is harmed by their lack of full acceptance. For instance, a verdict that an author's pet interpretation is untenable because it does not thor's pet interpretation is untenable because it does not provide for means to connect quantum mechanics to chaos theory, can still be countered easily by that author with a discussion about the value of this criterion itself: "my interpretation is metaphysically tenable and that is more important than providing the means to link up quantum mechanics with a silly little theory like chaos theory, isn't it?"

Thus philosophers of physics currently seem to lack the means for solving the selection problem as part of interpreting quantum mechanics. In order to make progress they need new acceptable and discriminating criteria for interpretations. They may arrive at such criteria by improving on the 'physics' criteria discussed in the previous paragraph. But philosophers of physics may also look for criteria in other fields. I now propose that engineering can provide for a new criterion: interpretations should accommodate the descriptions of artifacts employed by nano-engineers. The criterion demands minimally that interpretations should reproduce the conditionals $C \Rightarrow R$ implied by the functions ascribed to artifacts that are described by quantum mechanics (but it may demand more[16]). In this reading, the criterion is clear and can be accepted by philosophers of physics. Whether it is also discriminating is something to be determined by future research. Most interpretations of quantum mechanics can reproduce the conditional implied by the function ascribed to the teleportation decoder. But other examples of nanoscale artifacts may prove the proposed criterion to be more discriminating. The search for such examples is future research, and my guess is that nanoscale technology, when it takes off, will produce many of these examples. If the criterion is accepted, nano-engineers can thus help philosophers of physics select the tenable interpretations of quantum mechanics.

7. Conclusion

In my contribution I considered the consequence of describing technical artifacts by means of quantum mechanics. I gave an argument that this description can fail to accommodate the ascription of technical functions to those artifacts. This argument proceeded in five steps. Firstly I took the position that the ascription of a function to an artifact implies a conditional physical relation. A quantum-mechanical description of the artifact can then be said to accommodate the function ascription if it can reproduce this conditional. Secondly I presented the scheme of quantum teleportation and focused on the decoder that is part of the scheme. I showed that a quantum-mechanical description of teleportation can accommodate the function ascribed to this decoder. This positive result was conditioned upon the fact that the decoder is taken as a measurement device. Thirdly I argued that one can envisage a nanoscale version of quantum teleportation in which the decoder need not be a measurement device. The quantum-mechanical description of this nanoscale scheme cannot accommodate the function ascribed to the decoder.

I then showed that quantum-mechanical descriptions of artifacts can be turned into descriptions that do accommodate technical functions if nano-engineers adopt an interpretation of quantum mechanics: A conceptual gap that arises when artifacts are described quantum-mechanically can thus be closed by means provided by philosophers of physics. In this sense the use of quantum mechanics in nanoscale technology poses a challenge for the interpretations considered by philosophers of physics. Finally I reversed the order of assistance, and argued that nano-engineers can help philosophers of physics select tenable interpretations from the multitude of available interpretations of quantum mechanics. In philosophy of physics there already exist criteria that should be met by tenable interpretations, but these criteria are not sufficiently discriminating. I proposed a new criterion for tenable interpretations: interpretations of quantum mechanics should accommodate the descriptions of artifacts that are employed by engineers. This criterion demands minimally that interpretations should reproduce the conditionals implied by the function ascriptions to artifacts that are described by quantum mechanics. Further research has to decide whether this criterion is discriminating; the use of quantum mechanics in nanoscale technology thus poses a challenge also to nano-engineers, namely to come up with examples of function ascriptions to artifacts such that only a few interpretations can reproduce the implied conditionals. If the proposed criterion is accepted, a fruitful co-operation between nano-engineers and philosophers of physics will emerge: development of new nanoscale artifacts becomes intimately connected to singling out tenable interpretations of quantum mechanics.

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Notes

1. Drexler 1986, p. 14.
2. Drexler 1986, pp. 15 and 151-154.
3. When I speak of (technical) artifacts in this contribution, I always refer to material objects that are made to be used for practical purposes. I thus do not consider artistic artifacts such as paintings, nor non-material artifacts such as software and organizations.
4. Kroes *et al.* 2002.
5. *E.g.*, Baird 2002.
6. This first assumption ignores the unfortunately well-know phenomenon that we sometimes ascribe functions to technical artifacts that actually cannot perform them: a mower can temporarily lack the capacity to cut grass because it is broken, although we still take it as an object with the function of cutting grass. A consequence of this phenomenon is that the ascription of a function to an artifact need not imply that the artifact actually has the associated capacity. Houkes and Vermaas (2004) incorporate this phenomenon by formulating the first assumption as follows: the ascription of a function to an artifact implies that it is believed and justified that the artifact has this physical capacity. In this contribution I ignore the phenomenon by restricting the discussion to artifacts that do perform their functions.
7. I have drawn here on Mumford's (1995, Chapters 3 and 4) analysis of how ascriptions of categorical and dispositional properties entail (subjunctively) conditional relations. But I adopt this analysis only partly because Mumford characterizes these conditional relations as the 'functional roles' of the properties entailing them. I have to reject this characterization since it would make my position about what function ascriptions mean partly circular.
8. This analysis of technical functions relates function ascriptions to intentions of agents (Houkes and Vermaas 2004). The position I take thus coheres at least with some intentionalist accounts.
9. Because $p(\phi,A,a)$ is equal to 1, the Property Rule yields that after the measurement the system x indeed has the property 'A has value a' that corresponds to the outcome a of the measurement.
10. Hackermüller *et al.* 2003.
11. *E.g.*, Vermaas 1999.
12. *E.g.*, Bouwmeester *et al.* 2000 and Rieffel *et al.* 2000.
13. As announced in the introduction I ignore all quantum-mechanical details concerning the precise states of particles 1, 2 and 3, Alice's measurement and Bob's transformations. These details can be found in, for instance Rieffel *et al.* 2000 and Vermaas 2004.
14. *E.g.*, Bouwmeester *et al.* 1997, Boschi *et al.* 1998, and Nielsen *et al.* 1998.
15. For readers familiar with philosophy of physics terminology: when the signal is supposed to be sent from decoder to encoder, the (somewhat idealized) state of the channel is a degenerated improper mixture of eigenstates of the magnitude S. If the degeneracy is ignored, then many interpretations take this state as indicating that the channel has one of the properties 'S has value g_i' associated with the eigenstates.
16. For instance, engineers are known for their sketches of (envisaged) artifacts. One can take the criterion that interpretations accommodate technical descriptions as demanding also that they reproduce the properties represented in these sketches (Vermaas 2004).

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