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Space, Quantum Mechanics, and Bohm's Fish Tank

Jenann Ismael

There are complex pressures from many sources in physics for questioning whether space-time is a fundamental structure. Much of the impetus has come from considerations of cosmology and quantum gravity. ~~T~~heories of quantum gravity ~~almost all~~ describe fundamental structures that are significantly non-spatiotemporal. In that setting, the motivation comes from high-level theoretical concerns that are quite far removed from experience. Much of the discussion is highly technical and has not penetrated into the philosophical literature.[1] In philosophy, discussion of the possibility that space is not fundamental has centered on a particular proposal for the interpretation of quantum mechanics: David Albert's wave-function realism (Albert 1996, 2013). There, the discussion is conducted in the context of standard, non-relativistic quantum mechanics and is quite narrowly focused on whether the virtues of wave-function realism outweigh those of, say, GRW or Oxford Everett. The status of space on Albert's proposal has mostly been treated as a problem, and one that we would rather do without. There hasn't been, either in the physics literature or in the philosophical literature, a clear articulation of the general impetus provided by quantum phenomena for the move to an ontology in which space is recovered as an emergent structure. That is what I will try to provide.

I will suggest that there are signs in the most basic and familiar features of quantum phenomena that space (-time) is not fundamental. I will present simple low-dimensional examples that reproduce aspects of entanglement and complementarity and explore the difference between two kinds of explanation:one that looks for causal processes passing through the space in which the correlated events are situated, and one that derives them as lower dimensional projections of a higher dimensional reality.

The chapter is meant to display in a simple setting a form of explanation that connects quantum phenomena to questions about the status of space. For those who

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[1] That said, there is a significant, and growing, literature in the philosophy of quantum gravity that considers the reasons (in the context of quantum gravity generally, and within particular approaches) for treating spacetime as non-fundamental: e.g., Castellani & De Haro (this volume), Crowther (2016), Oriti (2014), Wüthrich (2019).

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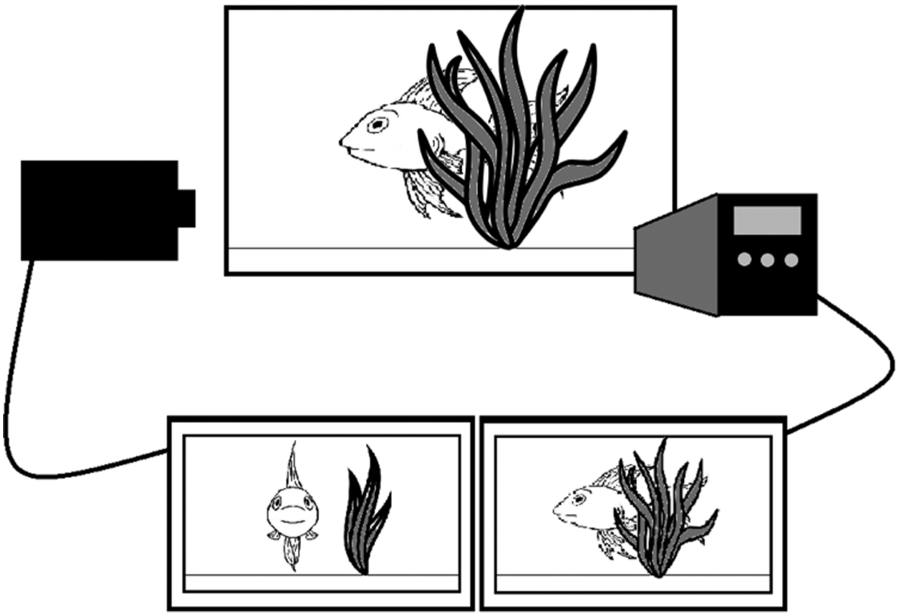

Figure 7.1 The set-up.

aren't soaked in the details of quantum mechanics, it is not easy to develop ~~the~~ physical intuition for what entanglement and complementarity are. The examples can serve as toy models that exhibit the connection between quantum phenomena and the (possible) non-fundamentality of space in a vivid way.[2] They also allow us to move ~~the~~ discussion in the foundational literature in philosophy away from wave-function realism, and also avoid some of the contested vocabulary.

The primary goal is to sharpen our understanding of what is at issue here. The division between those who advocate a non-(fundamentally) spatial account and those who insist that space has to be a fundamental structure touches on a deep, and increasingly pronounced divide between two ~~ways of ‘doing~~ metaphysics~~’~~.

7.1 Bohm's Fishtank and the Kaleidoscope

The first example comes from Bohm (with some embellishment) (see Figure 7.1).[3,4]

Imagine that there is a fish tank containing several multi-colored fish being filmed by one camera from the front and another camera from the side. It's an ordinary

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[2] Wave function realism (in the form in which it was originally proposed) is a first pass at this form of explanation. It was a bold initiative, and a radical departure from previous ways of thinking. But the case for treating space (time) as emergent should not be judged solely on its merits.

[3] The discussion here is non-relativistic and restricted to space. This is partly for visualizability and intuitive naturalness, but for other reasons as well. In a relativistic setting, it is more natural to treat space-time as the emergent structure, but time raises new questions, and I want to leave those aside.

[4] I've embellished the example and developed it more fully. Bohm presents it as a model of entanglement inBohm (1980).

three-dimensional tank. But suppose that the cameras project side-by-side images on a flat screen in an adjacent room, integrated seamlessly so that the screen displays just a two-dimensional expanse of color and moving shapes. Imagine someone whose experience was confined wholly to the shapes moving across the two-dimensional screen, who knew nothing directly about the three- dimensional space in which it (and he) was embedded, and who was keeping track of the on screen movements. Such a person would notice correlations between the images appearing on the two sides of the screen. For example, if on the right side of the screen he sees an image of a lionfish from the side, on the left side he will see another such image this time from the front. The two images will generally look different from one another. And we will suppose that if he focuses on either image by itself, he will not be able to predict its changes or movements from one moment to the next, but there will be interesting correlations between them. A flick of the tail or turn through an angle on the left will be mirrored by a flick of the tail and corresponding movement on the right. These correlations will seem to the viewer to be instantaneous. Someone whose experience was entirely confined to the two-dimensional images on screen would naturally try to fathom the mechanism by which the distant events communicate or influence one another. He might look for signals passing between them or search for causes in their common past. We know that the search would be misguided because the correlations aren't the product of signals or causal influences passing through the space of the screen. They are products of redundancy in the space in which the images of the fish appear which I'll call hereafter the *image-space*. The space in which the images of the fish appear is a lower dimensional projection of the space in which the fish themselves are contained. Where there is one fish in the tank, the viewer of the screen sees two. Where there is one tail flick he sees two. Objects and events located at a single place in the tank produce multiple copies at different places on the screen.

Another, more obvious example of correlations produced by redundancy in an image space can be obtained from a kaleidoscope. A kaleidoscope is an optical toy in a tube; it produces symmetrical patterns as mirrors reflect bits of colored glass. It consists of mirrors that run the full-length of the inside of the scope. There is a fixed or detachable object case at the end of the mirror tube that gives the scope its images. In many cases, the scope has a casing that contains glass beads that move freely and independently of one another inside the confines of the case. Changes in the configuration of beads produces changes in the pattern of light and color seen by someone looking through the eyepiece. The viewer doesn't directly see the three-dimensional beads or pieces of colored glass located in the casing. He sees those pieces reflected and refracted through the mirrors to produce a two-dimensional image in which each piece of glass is redundantly represented.

Facts about the way the scope is put together determine the invariant features of the image; its boundaries, symmetries, and topology.[5] The number and angles of

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[5] Invariant, that is, under transformations that don't disassemble the scope. These will appear as kinematic constraints on the space of possible images generated by a particular scope. The dynamics of the image space will simply describe its trajectory through the space of possible images.

the mirrors will determine the number of reflections viewed.[6] Someone looking through the lens wouldn't be able to predict which image will show up next, but he will notice correlations that would let him use what he observes in one part of the image space to get information about others. He will know that a blue triangle in one place will be matched and mirrored by counterparts in others. The symmetries are different in every case, but every case possesses them. The symmetries of a kaleidoscopic image space are more obvious than those of the fish tank. Viewers of the fish-screen focused on small-ish volumes of the space would see fish-images moving into and out of view and behaving like effectively autonomous two-dimensional realities. But for someone with a mathematical eye and a full view of the two screens, the symmetries of the fish image-space would be equally striking.

What is interesting about these examples is that we have a one–many correspondence between events in three-space and events in a non-fundamental image-space that express themselves as instantaneous dependencies between events at different image-space locations. Someone whose view was confined to the image space and who knew nothing of the higher dimensional reality in which they were embedded would be puzzled by the apparently coordinated randomness. He might posit causal mechanisms or signals passing between the two sides of the screen. But of course, as we know, no attempt to explain the correlations dynamically in the lower dimensional space will be correct. It's not that there is no explanation of the correlations. It is that there is no dynamical explanation *in the image space*. In the kaleidoscope example, the image that the observer sees when he looks through the eyeglass is two-dimensional, but the observer himself, the eyeglass, the bits of glass that generate the image, the placement of the mirrors and the process by which the bits of glass generate the image all live in three space. In the fish-tank example, the surface on which the redundant images of the fish project themselves is two-dimensional but the tank, the fish, the cameras, and the process by which the images on the screen are generated from the movements in the fish-tank, are three-dimensional. One may have an interest in producing a descriptive history of image space, but the *physics* is given in three dimensions. We wouldn't expect the screen to ~~be~~ autonomous, well-behaved dynamics. And no attempt to explain the correlations dynamically in the lower dimensional space will be correct.

The fish tank and the kaleidoscope provide low-dimensional examples of a way of explaining phenomena with suggestive similarities to the behavior of entangled particles quantum mechanics. In (standard, non-relativistic) quantum mechanics, the principles for constructing the state-spaces for complex systems—a pair of particles, an object system, and a measuring apparatus, an observer and her physical environment—generate states for the whole that cannot be reduced to states for the components. The result is that the quantum state of a complex system does not in

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[6] For a two-mirror system, a ten-degree angle, divided into 360, gives 35 reflections (or an 18-point star, since 18 of the reflections will be reversed from the original). A 45-degree angle divided into 360 degrees gives 7 reflections (or a 4-point star).

general permit decomposition into ontologically distinct components.[7] Schrödinger regarded entanglement as the defining trait of quantum theory, and it is the source of some of the central mysteries of quantum mechanics. The components of a system in an entangled state behave in ways that are individually unpredictable, but jointly constrained so that it is possible to forecast with certainty how one component will behave, given information about the measurements carried out on the other even though it is impossible to predict how they will behave individually and even though they are not interacting. The correlations borne by the spatially separated components of a system in an entangled state are well verified and there is no difficulty understanding how to derive them from the formalism. Difficulties surrounding entanglement have to do with trying to arrive at a physical understanding of how entangled particles manage to exhibit the coordinated randomness that the formalism predicts. It is in this connection that we get stories about tachyons, superluminal influence, or even cosmic conspiracy.

The ~~examples~~ present clearly visualizable models of cases in which observers see correlations that are the product of redundancy in the space in which the phenomena are arrayed rather than any real dynamical interaction. There are no signals or causal influences passing between the images, no dynamical interaction defined in image space that explains the correlations. And they suggest a way of seeing what is creating the difficulties in understanding the quantum analogues. Instead of seeing entangled systems as distinct existences interacting in a three-dimensional space (or events arranged in a four-dimensional space-time), we can see them as redundant glimpses of a deeper structure, refracted and reflected to provide multiple representations in the manifest space of everyday sense.

7.2 Complementarity

If Schrodinger regarded entanglement as the central mystery of quantum mechanics, others have seen complementarity as more fundamental. Questions of what the fundamental *objects* are, are of course bound up with questions of what the fundamental *quantities* are. Here I want to point to the relationship between 'observables' in the image space and beables in three-space.[8] Focus on the changing image of some particular fish as that fish turns through an angle; the aspect that was presented on the screen will disappear and be replaced by another. We can say that the view of a fish from one angle occludes another if they can appear on the screen individually but never together. A full frontal view completely occludes a view from the back; a left side view occludes the right, and so on (see Figure 7.2).

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[7] Or at least not in a way that preserves the logic of part and whole, that is to say that it doesn't permit decomposition into spatially localized components whose intrinsic states can be characterized independently of one another and then pieced together to obtain a complete description of the whole.

[8] Entanglement by itself doesn't suggest that the more fundamental space has to be *higher*-dimensional. It is complementarity (the commutation relations between quantum observables) that pushes us to a higher dimensional space. There are kaleidoscopes, for example, that don't have glass beads, but generate an image when pointed at a flat, colored surface.

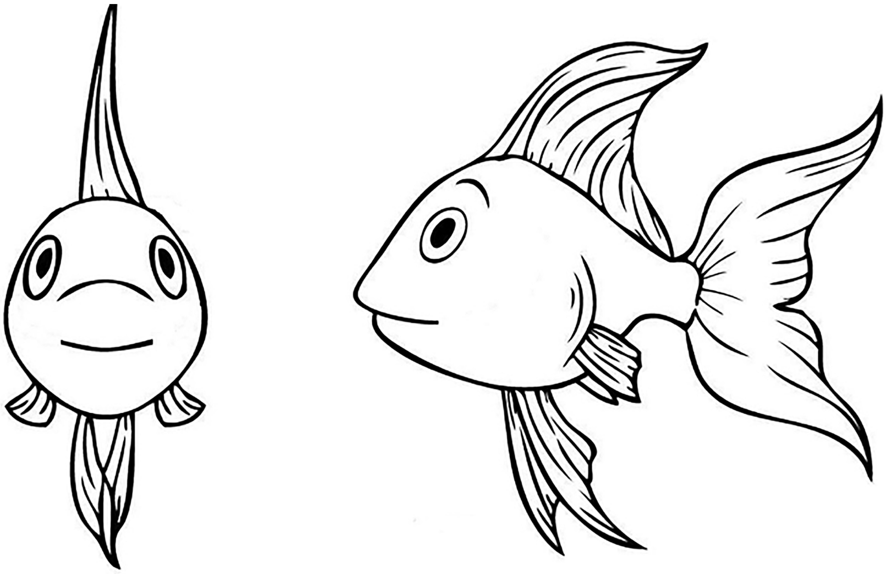

Figure 7.2 Front and side views of a fish.

These relations of mutual occlusion provide constraints on simultaneous observation~~s~~ of ~~different~~ images cast by fishes on the screen, and it would be natural to think of views that excluded one another as complementary. We can see what the back of a fish looks like and what the front looks like by turning the fish through an angle, but we can't simultaneously observe what the back and the front of the fish looks like. Those two images of the same fish never appear together on screen. There are also relations of partial occlusion. The frontal view obscures the side, so that you can't get a clear view of the side, when looking at the front, but maybe we can attach informative probabilities, given a frontal view of a fish, to what will be seen if it turns through an angle to expose its side. If these relations of full and partial occlusion were systematized, we would get a quite complex network of relations between two-dimensional fish-images. A full three-dimensional portrait could be pieced together from a collection of complementary, two-dimensional views if we understood how that collection was structured in three dimensions, something that we could read off of the relations of mutual occlusion. And conversely, if we had such a portrait, we would know everything there was to know about the images that the fish would project in image-space if it were turned through different angles.

Let us distinguish categorical from modal properties. Categorical properties are properties that involve no admixture of possibility. They describe what *is* the case, but not what *could*, *might*, or *would* be the case under some possible circumstance. Its disposition~~s~~ to decay under certain conditions ~~are~~ modal propert~~ies~~. The categorical description of a fish is properly given in three-dimensions, but the three-dimensional description embodies a good deal of complex, modal information about the images the fish *would* cast when viewed from different angles in image space.

Observations in image space correspond to image-space observables. The image a fish presents when viewed from angle **a** corresponds to the value it has for the observable 'view from **a**'. *We* know that the relations of occlusion and partial occlusion among image-space observables derive from the three-dimensional structure of the fish, but someone who didn't know that and who tried to interpret image-space observables as abiding properties of a two-dimensional object would run into trouble. In visual terms, he would end up with a Picasso-*esque* construction of two-dimensional images from different angles superimposed on top of one another in a geometrically impossible configuration. In mathematical terms, he would find that there is no reduced, categorical two-dimensional description that captures the invariant content of the information embodied in a three-dimensional description. He could express all of the information contained in a three-dimensional description in a wave-function-like mathematical object which embodied a lot of complex, modal information about the images the fish *would* cast in image space, i.e., about the 'values' of different 'image-space observables'. But it would be impossible to ground all of the dispositions that a fish has to appear thus and so when viewed from different angles in a ~~2d~~ description of how it *is*. The *categorical* description is irremediably three-dimensional.

And this is suggestive of the commutation relations among quantum observables. In classical mechanics, the space of possible states for an n-particle system is a 6n-dimensional space, usually parameterized by the positions and momenta of constituent particles. Any function of these basic variables is an observable~~. A~~nd every system always has a full set of values for all observables. The theory is defined by the axioms governing the behavior of the basic observables—Newton's equations for the positions or Hamilton's for positions and momenta. In (standard, non-relativistic) quantum mechanics, there is more structure on the set of quantities. The space of possible states is a Hilbert space. States are represented by vectors. Physical properties are represented by Hermitian operators on that space.[9] The dynamics is given by Schrodinger's equation, which describes the evolution of the state vector if undisturbed. The Eigenstate–Eigenvalue link tells us that we observe the value for observable A *iff* the vector representing its state is an eigenstate of the A-operator. Now, we know that for any Hermitian operator on a Hilbert space, there are others on the same space with which it doesn't share a full set of eigenvectors, and indeed some with which it has *no* eigenvectors in common. It follows that we can never observe simultaneous values for all observables and indeed that there are pairs of quantities whose values we never observe simultaneously. Quantities represented by operators that have no eigenstates in common are canonically conjugate. The most familiar example of such a pair are the position x and momentum p_x ~~in the x direction~~ of a point particle in one dimension. These relations of occlusion and partial occlusion are summarized by the Uncertainty relations given for the example just mentioned by, $[x,px] = i\hbar$

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[9] And the Hilbert space associated with a complex system is, of course, the tensor product of those associated with its components. The rule for constructing the state-spaces of complex systems is what gives rise to entangled states.

where $[x, px] = xpx - px, x$ is the commutator of x and p_x, i is the imaginary unit and $\hbar$ is the reduced Planck's constant $h/2\pi$.

As in the case of two dimensional fish-images, the relations take their most extreme form for canonically conjugate quantities, but if we catalogued them, we would find an interesting network of derivative relations of partial occlusion that would be preserved by free evolution or any attempt at measurement.

It is very natural to think that the uncertainty relations simply place epistemic constraints on simultaneous *knowledge* of a system's properties but that there must be some more categorical properties that characterize the intrinsic state of quantum systems and that ground the probabilistic dispositions attributed by the quantum state in the way that positions and momenta ground the dynamical dispositions of classical systems, and in the way that the categorical properties of any physical system ought to ground its law-governed behavioral dispositions. But we know a lot about the limits of this way of thinking in quantum mechanics. There has been a century of no-hidden variable results of varying strengths, placing restrictions on attempts to derive those law-governed dispositions from hidden, categorical properties of systems that live in three-space. Most people believe those restrictions are too strong to be met with empirical plausibility.[10] The claim is not that there has to be an intrinsic fact about a particle that determines how it will behave on any given occasion~~,~~ we are trying to introduce hidden variables that will allow us to say that there is an intrinsic difference between particles that have different law-governed dispositions to show a particular result in a measurement, or an intrinsic difference in a particular particle when it goes from having a chance of ½ to a chance of 1 of showing some result. We would expect analogous results if we tried to ground the information embodied in the 3-d description of a fish in categorical properties in two dimensions.

The suggestion here is that quantum observables do not behave like categorical properties of a three-dimensional system. If we can derive the commutation relations among quantum observables from categorical properties of objects that aren't ultimately localized in space, in a manner that mirrors the derivation of the algebra of two-dimensional aspects from the three-dimensional description of a fish, that would be an explanation of a quantum effect that should appeal to your sense of naturalness. Qualitatively and intuitively, one way of understanding the pathologies of quantum mechanics is that in quantum mechanics there is nowhere in three-space to *house*

[10] There are well-known loopholes. Noncontextual hidden variables theories~~,~~ assigning simultaneous values to all quantum mechanical observables~~,~~ are ruled out by Gleason and Kochen-Specker, contextual hidden variables theories~~,~~ in which a complete state assigns values to physical quantities only relative to contexts are left open. See Shimony (1984)for an especially illuminating discussion. We get an analogue of contextuality in the fish-tank example that is suggestive of what might be going on in the quantum case. To ground the dispositions embodied in the three-dimensional description of the fish in categorical properties in two dimensions, we have to relativize image-space observables to camera angles and positions (we say that a fish looks thus and so *from this or that angle*, but not *simpliciter*). This technique allows us to smuggle information about the three-dimensional configuration of the fish into two dimensions, but remains a purely formal option so long as camera positions and angles can't be specified in two-dimensions. Put another way, there's a failure of supervenience of measurable dispositions on (non-contextual) 2d observables defined over the image-space in the fish tank example because we lose information about relations between observables embodied in the three-dimensional structure of the fish and allowing contextuality is just a way of smuggling in 3-d information.

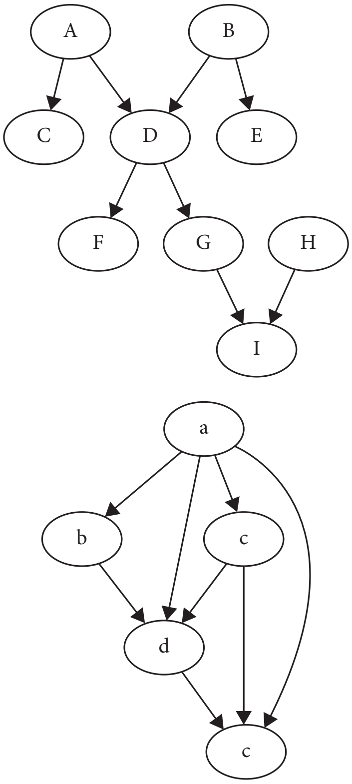

Figure 7.3 Examples of DAGS.

and *ground* the dispositions attributed by the quantum state. We have lacked an understanding of quantum systems that would explain in categorical terms the measurable dispositions they have to affect ourselves and our measuring instruments in ways that we can predict with statistical accuracy. Treating space-time as a derivative structure give us somewhere in the actual world to house and ground those dispositions.

The examples should not be over-interpreted. They provide toy models of specific phenomena, and were intended to give only a qualitative feel for how to connect those phenomena to the (non)-fundamentality of space. They don't substitute for a proper theory. They do, however, allow us to address some of the ambiguities that have hindered discussion of the quantum case.

7.3 Two Kinds of Causal Notions

We can distinguish two kinds of causal notions, both of which are familiar from the philosophical literature on causation. There are the causal relationships represented by directed, acyclic graphs (DAGs) and analyzed in terms of intervention counterfactuals (see Figures 7.3a and 7.3b).

These are introduced to distinguish causal structure from mere probabilistic correlation. One says that there is a causal relationship (as opposed to a mere probabilistic correlation) between X and Y just in case in an intervention on X would produce a change in Y (~~in technical terms,~~ when you wiggle X, Y wiggles). Then there are causal *processes*. These are chains of events called causal *interactions*, each of which involves the exchange of some conserved quantity. These are sometimes treated as competing accounts of causation, but we don't need to choose between the~~se~~. They are both useful, and in classical physics we find both. We have causal processes at the fundamental level, and manipulable causal relationships of the kind captured by DAGs all over the place. The~~se~~ are undiscriminating about levels, and neutral about underlying processes. They represent often local, scaffolded relationships among variables that can be investigated experimentally, frequently without knowledge of the underlying processes. They are part of what we might think of the surface phenomena of the world. Causal processes, by contrast, are part of the explanatory substructure. They relate fundamental parameters. They are local and continuous.

The early history of quantum mechanics interpretation was (in part) a search for causal processes to explain ~~of~~ entanglement, complementarity, and a suite of other effects that were slowly teased out of the quantum formalism and put on display. The quantum formalism as it stood was recognized as an elegant, compact, and precise embodiment of the regular, law-governed effects of quantum systems on macroscopic, spatially localized 'measuring' instruments. But people were looking for an understanding of the causal processes in space-time that produced quantum effects. They were hankering after (to use a nice phrase from Bell) an account of what goes on in 'the limbo between one observation and another' (Bell 1985; Butterfield 1992).

As the~~se~~ got increasingly strained and unnatural, and as the quantum formalism frustrated them systematically, and as no-go theorems of increasing strength made them seem more and more like perversions of a formalism that had its own inner logic, people started to deny the need for a causal process explanation (Hughes 1992; Bub 2016; Healey 2017a; Spekkens 2007; Fuchs, Mermin, and Schack 2014). Alongside approaches to quantum mechanics that renounced the search for a quantum ontology, there were those who continued the search, but made radical departures from classical ontology.[11]All the while, of course, there were still people who were doing the more traditional kind of quantum ontology (GRW, Bohmian Mechanics).[12] The people I'm talking about here were all people who were reacting to the frustrated attempts to fill in the limbo between experiments with continuous trajectories and causal processes.

The landscape of possibilities here has become increasingly developed and refined. Against this background, what the toy models suggest is a way of hanging onto all of the causal relationships that we find in space-time, but instead of looking for microscopic causal processes propagating through space-time, we look for a substructure

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[11] Albert (1996, 2013)and the Everettians, well represented in Wallace (2012).

[12] See Lewis (2016) for an overview.

of connections behind the scenes, threading connections through degrees of freedom that aren't themselves localized in space.

7.4 Two Notions of Space

Just as we can distinguish two notions of causation, we can discern two notions of space. Let's use **Our-space** to refer to the manifest space of everyday sense and **Ur-space** to refer to the space in which the fundamental particulars are housed or, if you like this way of speaking: the space that acts as the ground of individuation for the fundamental objects, or perhaps the space in which the world decomposes into separable parts. Each of these ways of speaking evokes a role that Our-space plays in classical physics.[13] Then question is, then, whether we should see the kinds of connections that the quantum formalism predicts ~~about~~ local beables in Our-space as suggesting the existence of a more fundamental ordering, an Ur-space containing beables whose connections to space-time ~~be~~ables screens off the connections among ~~Our-space beables~~.

The symmetry of the connection between the particles in a Bell experiment (or the parts of an entangled system), the absence of evident mediating processes, the complex relations of full and partial occlusion among space-time observables, the fact that the quantum state contains more information than can ever be directly accessed in measurements in space-time all suddenly make sense if Our-space has the status of an image space. They all snap into place, as exactly what is to be expected. The difficulties that we find in attempts to fill in the story about what goes on in the limbo between experiments with continuous trajectories and causal processes in space-time ~~these~~ have analogues in the examples for observers in the examples trying to do their physics in the image spaces.

7.5 The Rationale for Moving to Ur-Space

In the contemporary literature surrounding the discussion of wave function realism, there are two sorts of questions that have been distilled out of the controversy, both pressed here by Wayne Myrvold, in a symposium on Albert's ~~most recent book:~~

> The general precept at work here seems to be . . . Faced with a physical theory that, taken at face value, seems to violate the condition of separability [i.e., the requirement that there should be no connections between systems located in different parts of space that aren't mediated by causal processes], we are to find (or construct) another space, such that states of the theory can represented as assignment of local quantities to points in that space, and to take some space of this sort as the fundamental space of the theory. If this is the precept in operation, then I have two sorts of question about it. One is: in what sense is a space of this sort . . . more fundamental than the space in which we live and move . . . [and what is the] argument in favour of separability as a requirement on an acceptable theory of fundamental physics. (Myrvold2016)

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[13] The reference here is to Gareth Evans' (1982) discussion of the role of space as the fundamental ground of individuation of objects. Evans is talking about the role that Our-space plays in the conceptual scheme of common sense.

The toy models can help us address Myrvold's questions. First they give us concrete, low-dimensional examples of the sort of relationship that is being proposed to hold between Our-space and an Ur-space. The philosophical discussion about what it means to say that space is (or is not) fundamental has been rather cloudy. It turns inward to reflection on what 'fundamental' means, then to analysis of the various roles that space plays in our experience, on the one hand, and in physics, on the other. Worries are voiced that on this proposal space would turn to be 'unreal' or 'illusory', and we begin to worry what 'real' means. This is useful in helping us refine our concepts, but it hasn't helped to clarify the physical proposal.[14]

The toy models can at once make the proposal ~~both~~ concrete without using that vocabulary, and serve as the basis for refining it. And they make the rationale explicit by highlighting the sorts of clues to which people are responding when they look to a non-spatiotemporal substructure. Kerry Mckenzie in a recent review discussing Albert's ~~view~~ puts the demand for the rationale more spiritedly. She writes that Albert's view:

> Seems to be embraced by those who do so . . . only in order that we not be 'saddled' with the 'old-fashioned and unwelcome quantum mechanical weirdness of non-separability' . . . it seems deeply incongruous to me that respectable philosophers of physics are so sanguine about letting quasi-aesthetic predilections like this do so much ontological work. . . . There is no reflection, not so much as a momentary expression of regret, over the idea that at some point we may have no choice but to retreat to largely individual preferences regarding virtues to support our world view. (McKenzie 2016)

I ~~have been~~ suggesting that the case for this *form* of explanation can be made independently of wave-function realism~~. It~~ is not a mere 'intuition', expectation derived from classical habits of thought, or 'quasi-aesthetic' distaste for non-separability that motivate this ~~exploration~~ but clues in the phenomena of a kind that are our best guide to the deep structure of the world.

The rationale for suspecting that there might be a structure behind (or underneath) space-time that explains the deepest quantum effects is not a perverse predilection for revisionary metaphysics, a 'quasi-aesthetic' distaste for non-separability. The complex connections between the events in different parts of space revealed by the quantum formalism are the same kinds of clues that guide us in other kinds of inferences when we look for an explanatory structure. That is why they appeal to our sense of explanatory naturalness. It would be nice here, if we could invoke a formal normative framework for scientific inference so that we wouldn't have to rely on our sense of explanatory naturalness, but ~~the fact is that~~ we don't. Our sense of explanatory naturalness plays an ineliminable role both in science and in everyday inference to the best explanation.

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[14] This is one of the most important reasons for getting away from abstract, verbal presentations. Words like 'fundamental' and 'emergent' don't have a clearly defined meaning in current philosophical usage. In physics, and as I will use them here, 'fundamental' means 'basic in the ontological ordering', and 'emergent' means 'not fundamental'. But as soon as one moves outside those circles the terms are used in ways that are complex and contested. Even without a well-defined meaning, the terms are laden with misleading philosophical connotations. On the question of whether space is 'illusory' if not fundamental, see Lewis (2004, 2013).

Once the ambiguities in the central notions are resolved, it begins to emerge that what separates the two sides of the debate is a very deep division between two ways of doing metaphysics. On the one hand, there is the purist (represented here by David Albert, and elsewhere by people like David Wallace (2012) and myself) whose standards for ontology are mathematical clues that guide physics at the fundamental level. On the other hand, there is the a priori metaphysician whose standards are closeness to common sense. The standards for choosing between fundamental ontologies in physics are the kinds of formal clues that I have highlighted here, and that push in the direction of an Ur-space;one that plays the same role in individuation in fundamental ontology that Our-space plays in individuation of the ontology of common sense, but which is not three-dimensional.

7.6 Reichenbach's Cube

I want to add here, one last example. This one drawn from Reichenbach. It comes from *Experience and Prediction*.[15] It is not a quantum example. Reichenbach ~~writes~~:

> ~~Imagine~~ a world in which the whole of mankind is imprisoned in a huge cube, the walls on which are made of sheets of white cloth, translucent as the screen of a cinema but not permeable by direct light rays. Outside this cube there live birds, the shadows of which are projected on the ceiling of the cube by the sunrays; on account of the translucent character of this screen, the shadow-figures of the birds can be seen by the men within the cube. The birds themselves cannot be seen, and their singing cannot be heard. To introduce the second set of shadow-figures on the vertical plane, we image a system of mirrors outside the cube which a friendly ghost has constructed in such a way that a second system of light rays running horizontally projects shadow-figures of the birds on one of the vertical walls of the cube . . . this invisible friend of mankind . . . leaves [those inside the cube] to their own observations and waits to see whether they will discover the birds outside. (pp. 115–16)

Penetration through the walls is impossible, so all that they have to go on is correlations in the movements of the shadows, and as Reichenbach observes:

> If the shade a1 wags its tail, then the shade a2 also wags its tail at the same moment. Sometimes there are fights among the shades; then, if a1 is in a fight with b1, a2 is always simultaneously in a fight with b2. (p. 118)

The story has a hero—unsurprisingly called 'Copernicus'—who propose~~d~~ a radical and suggestive theory.

> He will maintain that the strange correspondence between the two shad~~e~~s of one pair cannot be a matter of chance but that these two shad~~e~~s are nothing but effects caused by one individual thing situated outside the cube within free space. He calls these things 'birds' and says that these are animals flying outside the cube, different from the shadow-figures, having an existence of their own, and that the black spots are nothing but shadows. (p. 118)

The example has the same form as Bohm's fish tank. It occurs in the context of a discussion of the inference from cross modal patterns in sensory phenomena to the

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[15] Reichenbach (1938). There is a very nice formal discussion by Elliot Sober (2011) that connects it to common cause reasoning.

existence of an external world. And that analogy is apt here as well. In each of these cases, we trace correlations to a common source.[16] We have links between 'images' or 'shadows', which have a secondary existence, connections among which are not explained by causal processes that pass through the space in they live, but common links to something outside the space in which the images are projected. The suggestion is that these same inference patterns are pointing towards treating Our-space as something less than fundamental.

These are the kinds of signs that usually lead ~~us~~ to a search for degrees of freedom that screen off the connection. What is special about the quantum case is that those degrees of freedom can't be assigned to volumes of space in the natural and familiar way (viz., as representing non-contextual, intrinsic properties whose effect on other regions is mediated by local influences).[17] The way to think of the epistemic position of the theori~~es~~ is that she is solving simultaneous equations for the degrees of freedom controlling a range of observable effects, where the nature of those degrees of freedom is itself up for grabs.[18] This is what is going on in the example that Reichenbach was pointing to the inference from correlations across sensory streams to an external world.[19] In *micro*physics, the data streams are instrumentally mediated sources of information about a world whose ultimate structure is inferred, and the hope is to approach understanding of the basic elements of nature at least up to the level to which our instruments are able to probe. We form an increasingly articulate understanding of the unobservable substructure of the world as we learn to distinguish separable components, isolate their individual ranges of motion and see how their joint movements produce the visible ~~motion~~. The clues that we use in these cases are the same ones to which we are responding in these everyday inferences. We

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[16] It might seem surprising that Reichenbach does not try to justify this as an instance of his Common Cause Principle. That Principle received its most explicit defense in his (posthumously published) 1956 book, *The Direction of Time* (Reichenbach 1956). The discussion in *Experience and Prediction* was published in 1949. It would be interesting to know more about the trajectory of his thought in this period.

[17] The idea that there are degrees of freedom that screen off the connection between particles in entangled states is not new. Many people have suggested that we should just think of the quantum state as containing information about degrees of freedom that don't have a spatiotemporal location, or can't be localized in any volume of space. In formal terms, that is a natural thing to say. The wave-function contains information about degrees of freedom that can't be localized. The problem is that if we allow causal agents outside of space, we break the connection between space and causal structure that we have in a classical setting. The suggestion here is that Ur-space just *is* the space that makes the causal structure explicit. The role played in a classical setting by Our-space is played in this setting by Ur-space.

[18] Consider a doctor trying to explain an array of co-presenting symptoms. She doesn't start out with a clear and distinct idea of the source (is it microbe? a tumor? an unknown disease?), but there is a default assumption that if the symptoms always present together they probably have a common source. In that case, she can open up the body and check her hypothesis. In physics, this kind of direct verification is not an option. We are like fisherman trying to figure out what is producing ripples on the surface of an opaque body of water, we can send down lines and probes, but we can't go down there and check our hypotheses. We rely unavoidably on heavily mediated information streams, and it is our theories that individuate their source.

[19] We don't (of course) make that inference consciously. It is made (effectively) by the brain in processing sensory clues for spatially structured perceptual presentations. Reichenbach is seeking here simply to make the structure of the inference explicit.

look at mutual constraints on independent variation as symptoms of redundancy in our information and use them to triangulate to a common source.[20]

7.7 Shifting the Intuitive Weight

There are two ontological attitudes one can take in approaching the interpretation of quantum mechanics. One assumes a broadly classical ontology of three-dimensional objects (particles, configurations of particles, or macroscopic measuring devices, as the case may be) and supposes that the quantum laws describe how the categorical properties of these objects change over time. The other attitude turns that story on its head. On this view, what we see in three-space, are mere appearances: i.e., partial and perhaps redundant ~~represen~~tations of a reality whose intrinsic structure is unknown. Correlations trace to underlying identities, dispositions are grounded in categorical properties, the three-dimensional space of classical physics (or four-dimensional space-time of relativistic physics) is recovered as a derivative structure.

In practical terms, making the gestalt shift from the first to the second attitude means abandoning the idea that there should be a well-behaved story about what happens in three-space, calling off the search for a physical process in space-time by which the components of an entangled system influence one another, relinquishing the call for continuous trajectories and rejecting any attempt to describe what is happening in three-space in the gaps between measurements. It has a rather different explanatory task:recovering what we see in three-space from a deeper structure. The two *styles* of explanation are very different. One asks ‘what are the processes in space-time that explain the correlations?’ The other asks ‘how do correlations in space-time emerge from the structure of the underlying reality?’

Many parts of physics have made this shift already. In cosmology, and quantum gravity, as I said, it is routine to treat space (and perhaps space-time) as a derivative structure. The reasons are complex, and more highly theoretical.[21] The physics, as always, proceeds under its own steam. But the philosophical imagination is lagging behind. That is in part because the philosophical imagination tends to be guided by common sense, and not by the kinds of formal clues that I have been pointing to here. My colleague Richard Healey is fond of saying that if we want to know what physics is telling us about the world, we should be looking at our best and most fundamental theories:quantum field theory, or quantum gravity, certainly standard, non-relativistic quantum mechanics. He’s right about that. But it is still worth looking back and seeing whether we can see suggestions of a non-spatiotemporal order even in the most familiar and elementary quantum phenomena, the ones that are at the heart of the difference between the classical and quantum world.

Whether an approach like this works will remain to be seen. Ultimately, these are physical questions. They won’t be settled by philosophical argument, but by calculation and experiment, and the detailed development of theory.

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[20] If criteria of identity for underlying beables are given independently, the situation is different. So it is really only when we have no independent criteria of identity for the underlying beables that these kinds of constraints guide individuation, favoring redundancy over coincidence.

[21] See Wüthrich and Huggett (2013) as well as the references in note 1.